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ERROR PROTECTION OF STORES
MANAGEMENT SYSTEM DATA
TRANSFERS

THESIS

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ERROR PROTECTION OF STORES MANAGEMENT SYSTEM DATA TRANSFERS

THESIS

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by

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Paul F. Miller

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Abstract

Stores management systems are being converted from analog control to digital control. The DOD has chosen the MIL-STD-1553B multiplexed digital data bus as the communication channel for the digital stores management system. However, there is insufficient error protection inherent in MIL-STD-1553B to ensure reliable transfer of critical commands. This paper examines possible methods of improving the performance of the system within the constraints of MIL-STD-1553B.

To achieve better performance (measured in probability of error and throughput), a combination of channel codes and specific transmission schemes are evaluated. Word error rates and block (message) error rates are calculated for each coding scheme. The block error rates are then used to determine the performance of each specific coding scheme-transmission scheme pair. Finally, the coding scheme-transmission scheme pairs are compared for probability of error and throughput.

The analysis assumes independent random errors. All calculations are done for a range of bit error rates (10^{-4} to 10^{-7}). Also included in this report is a method of implementing each coding scheme within the constraints of MIL-STD-1553B.

ERROR PROTECTION OF STORES MANAGEMENT SYSTEM

DATA TRANSFERS

I. Introduction

Background

In many newer aircraft and especially in future aircraft, many of the control functions are being changed from analog control to digital control. One of the areas that is changing is the management of aircraft stores. (Aircraft stores are anything that temporarily hangs from the aircraft, i.e., bombs, rockets, fuel cells, ECM pods.) The change to a digital controlling signal requires a concurrent change in the communication channel required to convey the information from the controlling source to the actual user. For digital signals, the Department of Defense has chosen the MIL-STD-1553B multiplexed digital data bus to be the communication channel. The MIL-STD-1553B data bus has some error protection capabilities (see Appendix A). However, some data transfers in aircraft stores management are very critical (i.e., arming or firing commands) and must be processed so as to ensure minimum chances of error in communication. The MIL-STD-1553B data bus does not have sufficient error protection capability to ensure the correct reception of these critical data transfers. Therefore, more error protection of these critical data transfers is required.

Problem

The problem addressed in this thesis is the determination of a means of providing the additional error protection necessary to ensure the correct reception of critical data transfers. However, any error protection scheme must be implemented within the framework of MIL-STD-1553B. The proposed error protection schemes are evaluated for their effectiveness in reducing transmission errors and their effect on the throughput of the system. Also, the impact of the proposed error protection schemes on system hardware and software complexity must be evaluated.

Although burst errors may be a problem in this channel, they are not analyzed in this thesis. The channel is modeled as producing only independent random errors (i.e., a memoryless channel). Later, the results of this thesis can be extended to include burst errors. To generalize the applicability of this thesis, results are found for a range of bit error rates rather than one specific bit error rate. Then, when an experimental bit error rate is determined, the approximate results will already be known.

Solution

The solution to this problem is providing additional error protection. The additional error protection consists of two parts: (1) a channel coding scheme, and (2) a transmission scheme. The combination of the two yields increased error detection and/or error correction. The channel coding schemes are discussed in Chapter II and the transmission schemes are analyzed in Chapters III through VI.

Chapter II deals with the channel coding schemes utilized in this thesis. Hamming codes and BCH codes are used (in conjunction with the transmission schemes) to improve the error protection capabilities of the system. Word error rates are calculated for each of the coding schemes and for MIL-STD-1553B with no additional error protection. Using these word error rates, block error probabilities are found for the two coding schemes and the MIL-STD. The probabilities are found for a range of bit error rates as previously mentioned. The block error probabilities are then used in Chapters III through VI to evaluate the overall system performance for the various coding scheme-transmission scheme pairs. Also in Chapter II, the method for implementing each coding scheme within the framework of MIL-STD-1553B is discussed.

Chapters III through VI contain the analysis of the various transmission schemes. Each of the schemes is analyzed to determine the system throughput and the system's overall probability of error. The simplest transmission scheme, Stop-and-Wait ARQ (Automatic Repeat Request) is discussed in Chapter III. MIL-STD-1553B with no additional error protection is evaluated in Chapter IV. A hybrid transmission scheme is analyzed in Chapter V. A hybrid scheme is a combination of FEC (Forward Error Correcting) and ARQ transmission schemes. Finally, Chapter VI contains the 'pure FEC' transmission scheme analysis. One other widely used transmission scheme, Go-Back-N ARQ cannot be used within the framework of MIL-STD-1553B. The standard data bus operates in a command/response mode, which is unconducive to Go-Back-N ARQ. Even if Go-Back-N ARQ could be integrated into the MIL-STD-1553B framework,

the buffering requirements would be immense and the hardware cost would preclude the use of this transmission scheme.

Finally, in Chapter VII, the results of all of the analyses are compared. The transmission scheme-coding scheme pairs are compared on a basis of throughput and overall probability of error. Also a figure of merit is included to compare the complexity (in hardware and software) of each scheme. No recommendations regarding the best systems are made in this thesis; instead, the analysis is done and the results are contrasted. Thus, the system designer may choose the error protection scheme that will provide the best performance for a specific system.

II Calculation of Word Error Rates and Block Error Rates

Introduction

To effectively evaluate the quality of various coding schemes, the schemes must be evaluated on some common ground. In this thesis, the common ground is system throughput and overall probability of error. An intermediate step in these calculations is calculating the word error rates and block error rates for various coding schemes. In this chapter word error rates and block error rates are derived for the MIL-STD-1553B data bus with no error protection and using either a Hamming or a BCH encoding scheme. The calculations described in this chapter are basic to coding theory. Calculations similar to these can be found in any introductory coding theory text such as the texts by Gallager (Ref 6), Lin (Ref 7), and Peterson and Weldon (Ref 11).

When a word is decoded, it will fall into one of three possible categories:

1. it will be decoded correctly;
2. an error will be detected but not corrected; or
3. an error will be undetected.

These three events partition the sample space of possible outcomes. The events can be written probabalistically as:

PNE $\hat{=}$ probability of no error (including corrected errors)

PDE $\hat{=}$ probability of a detected error

PUE $\hat{=}$ probability of an undetected error

and because of the partition

$$PNE + PDE + PUE = 1 \qquad (1)$$

With knowledge of the coding schemes, knowledge of MIL-STD-1553B, and knowledge of the bit error rate, the word error rates can be found for any of the coding schemes. The probability of a bit error is denoted as p_e in this thesis. Rather than evaluate all the coding schemes with a certain p_e, this thesis evaluates the coding scheme for a range of p_e's. Therefore, a range of values is obtained for each word error rate of each coding scheme. MIL-STD-1553B with no error protection will be evaluated first, followed by the Hamming encoding scheme and the BCH encoding scheme. The Hamming scheme corrects single bit errors and detects double bit errors. It will be used in a hybrid ARQ configuration. The BCH codes will be used in several configurations: either in error detection, error correction, or combined error detection and error correction.

MIL-STD-1553B Without Additional Error Protection

According to MIL-STD-1553B, each word consists of a sync waveform, 16 information bits, and one parity bit. The single parity bit detects any odd number of errors. Therefore, MIL-STD-1553B (without additional error protection) will detect odd numbers of bit errors, will not detect even numbers of bit errors, and will operate correctly only if there are no bit errors. Thus, the calculation of word error rates for this case is relatively straightforward.

The probability that the word is received correctly (PNE) is the probability that all 17 bits are received correctly. The probability

that a single bit is received correctly is $1 - p_e$, and since errors are independent each of the 17 bits will be correct with the same probability. Then the probability of correct word reception is the product of the probabilities of the correct reception of each bit. Therefore, the probability that a word is received correctly is

$$PNE = (1 - p_e)^{17} \tag{2}$$

Because there is a single parity bit in MIL-STD-1553B, any odd number of errors will be detected. Therefore, the probability of a detected error (PDE) is the sum of the probabilities of all odd error patterns. For a given word that contains n errors, $17 - n$ bits will be correct and n bits will be in error. Thus, the probability of a word containing n errors is

$$(1 - p_e)^{17-n} (p_e)^n \tag{3}$$

However, there are several ways to get n errors in a word. For example, if $n = 1$, there are 17 ways to get a single error--the error could occur in any one of the 17 bits. Then the probability of getting one error in a word is $17(1 - p_e)^{16} p_e^{\,1}$. In general, the number of ways of getting n errors in a 17 bit word is

$$\binom{17}{n} = \frac{17!}{n!\ (17 - n)!} \tag{4}$$

$$\text{e.g.,} \quad \binom{17}{1} = \frac{17!}{1!\ 16!} = \frac{17}{1} = 17$$

The probability of a word containing n errors is given in Eq (3). The total number of possible words containing n errors can be calculated with Eq (4). Thus, the probability of getting n errors in any word is

$$\binom{17}{n} \ (1 - p_e)^{17-n} \ (p_e)^n \tag{5}$$

Since any odd number of errors will cause a detected error, the sum of the probabilities of all odd error patterns will equal the probability of a detected error (PDE). Hence,

$$PDE = \sum_{\substack{n=1,3,5,\\ \dots,17}} \binom{17}{n} \ (1 - p_e)^{17-n} \ (p_e)^n \tag{6}$$

Similarly, all even error patterns will be undetected. The analysis for the probability of an undetected error (PUE) is the same as for PDE except n is even. Thus,

$$PUE = \sum_{\substack{n=2,4,6,\\ \dots,16}} \binom{17}{n} \ (1 - p_e)^{17-n} \ (p_e)^n \tag{7}$$

<u>Hamming Codes</u>

This coding scheme will correct all single-bit errors and detect all two-bit errors. The command word is encoded using an (8,4) Hamming code with the parity bits in the first data word. The data is encoded using a (16,11) Hamming code. The format for encoding the command word is shown in Figure 1. All the information bits must remain in the first word since it is the MIL-STD-1553B command word and its format cannot be changed. The 16 information bits of the command word are divided into four groups of 4 bits each. Then each

4 bit group is encoded with a (8,4) Hamming code. The 16 resulting parity bits (four groups of 4 bits each) are put into the first data word following the command word.

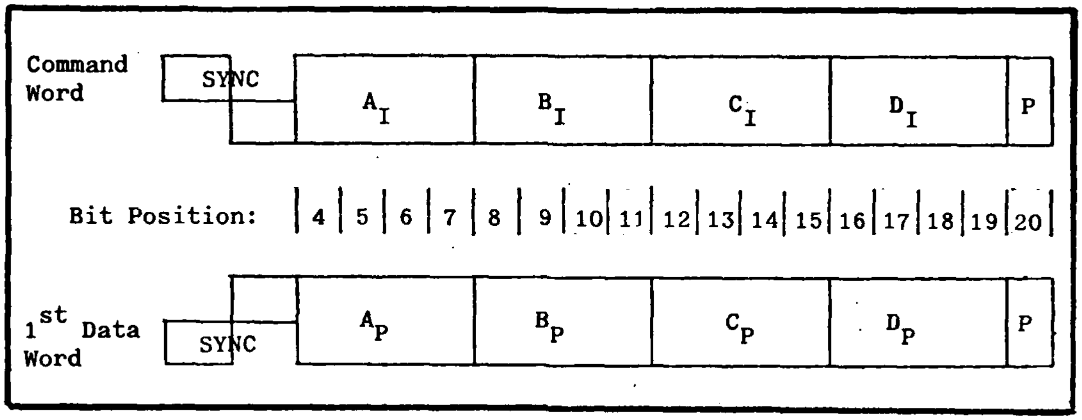


Figure 1. Command Word - Data Word Pair Using the (8,4) Hamming Code

where: P = MIL-STD-1553B parity bit

SYNC = three bit synchronization signal

and the subscripts indicate:

I = information bits of the (8,4) Hamming code

P = parity bits of the (8,4) Hamming code

This accounts for the command word and the first data word of each message. However, since each message may have a maximum of 32 data words, there are still 31 data words which must be encoded. Each of these data words is encoded using a (16,11) Hamming code. This code consists of 11 information bits and 5 parity bits. This scheme makes maximum use of the 16 bit free format information field in the data word (see Figure 2).

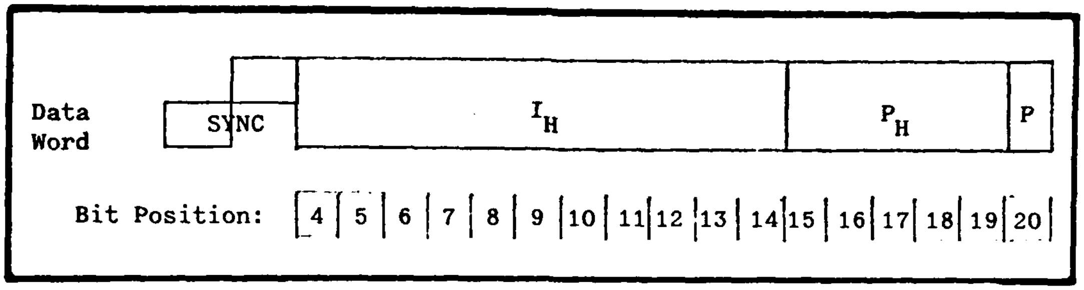


Figure 2. Data Word Using the (16,11) Hamming Code

where: I_H = the 11 information bits of the (16,11) Hamming code

P_H = the 5 parity bits of the (16,11) Hamming code

P = MIL-STD-1553B parity bit

SYNC = the three bit synchronization signal

The maximum total message consists of one command word and 32 data words. However, one of the data words contains the command word's parity checks. Therefore, only 31 data words contain information. Each encoded data word has 11 information bits; therefore, the maximum message contains $31 \times 11 = 341$ bits of information. Without additional error protection, MIL-STD-1553B allows 32 data words of 16 bits each for a maximum message length of 512 bits. The Hamming encoding reduces the maximum message length to approximately 2/3 the original value. The effect of this on throughput will be seen later.

Data Words - (16,11) Hamming Codes. The calculation of word error rates is relatively straightforward for the (16,11) Hamming encoded data words. The MIL-STD parity check bit is not used in the (16,11) Hamming code; however, the parity bit can be used to increase the probability of a detected error because it will detect any number of odd errors.

The probability that the correct action is taken (PNE) is the probability that all bits are received correctly plus, since this code corrects single errors, the probability that any single error occurs. The probability that a single bit is correct is $1 - p_e$. Therefore, the probability that all 16 bits are correct is $(1 - p_e)^{16}$. A single bit is in error with probability p_e ; thus, the probability that a word contains one error is $(1 - p_e)^{15} (p_e)$. However, there are $\binom{16}{1} = 16$ possible ways of getting a single error. Therefore, the probability that the correct action is taken is:

$$PNE = (1 - p_e)^{16} + 16(1 - p_e)^{15} p_e \qquad (8)$$

The (16,11) Hamming code detects any two bit error patterns. In addition, the MIL-STD parity bit independently detects any odd number of errors. Therefore, the probability of a detected error (PDE) is the probability that two errors occur in the 16 encoded bits plus the probability that any odd number of errors, three or greater, occur in the word. Similarly, the probability of an undetected error (PUE) is the probability that any even number of errors, four or greater, occur in the word. Note that the probability of an error occurring in the parity bit is the same as the probability of a bit error in any position. Recall that the probability of a certain number of errors occurring in the 16 encoded bits is $\binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}$. It follows that the probability of odd errors, three or greater, in the 16 encoded bits is $\sum_{n=3,5,7,\ldots,17} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}$. Then, if the MIL-STD parity bit is correct, an odd number of errors has occurred and the error will be detected. However, if the MIL-STD parity bit is incorrect, an even

number of errors has occurred and the error will be undetected. Thus, for odd n, a detected error occurs with probability:

$$\sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}(1 - p_e)$$

$$= \sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{17-n} p_e^{\,n} \qquad (9)$$

and an undetected error occurs with probability:

$$\sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}(p_e)$$

$$= \sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n+1} \qquad (10)$$

Similarly, for even n, a detected error occurs with probability:

$$\sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}(p_e)$$

$$= \sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n+1} \qquad (11)$$

and an undetected error occurs with probability:

$$\sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n}(1 - p_e)$$

$$= \sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{17-n} p_e^{\,n} \qquad (12)$$

Recall that the Hamming code will detect any two bit errors within the 16 encoded bits. The probability of a two bit error is given by

$$\binom{16}{2} (1 - p_e)^{14} p_e^{\,2} = 120(1 - p_e)^{14} p_e^{\,2} \qquad (13)$$

Combining Eqs (9), (11), and (13) yields the probability of a detected error in a (16,11) Hamming encoded data word.

$$\text{PDE} = 120(1 - p_e)^{14} p_e^{\,2} + \sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{17-n} p_e^{\,n}$$

$$+ \sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n+1} \qquad (14)$$

The probability of an undetected error in a (16,11) Hamming encoded data word is given in Eq (15). It is the sum of Eqs (10) and (12).

$$\text{PUE} = \sum_{\substack{n=3,5,7,\\ \ldots,15}} \binom{16}{n} (1 - p_e)^{16-n} p_e^{\,n+1}$$

$$+ \sum_{\substack{n=4,6,8,\\ \ldots,16}} \binom{16}{n} (1 - p_e)^{17-n} p_e^{\,n} \qquad (15)$$

Command Word - (8,4) Hamming Code. The word error rates are harder to calculate for the (8,4) Hamming code because there are four Hamming encoded words within two MIL-STD-1553B words. As shown in Figure 1, each letter group is an independent (8,4) Hamming codeword with the 4 information bits in the first word and the 4 parity bits in the

second word. This causes not only the number of errors, but also the distribution of the errors to affect the decoding. For example, two bit errors can result in either a detected error or a corrected error. If (see Figure 1) both errors are in one of the letter groups, then a two bit detected error occurs. If one error is in each of two letter groups, e.g., A and D, then two single errors occur, the errors are corrected, and the words are correctly interpreted. Note that the error rates are calculated for a pair of MIL-STD-1553B words. The error rates for these two-word combinations will be denoted: PNE2, PDE2, and PUE2 respectively for correctable, detectable, and undetectable errors. The fact that these rates are for two words while the (16,11) Hamming code error rates are for one word presents no problem because the difference will be accounted for when block error rates are calculated at the end of this chapter.

A good place to start is calculation of the probability of taking the correct action (PNE2). The correct action will be taken if no errors occur or if only correctable errors occur. In other words, PNE equals the probability of zero errors plus the probability of a maximum of one error in each letter group. One error in any letter group is correctable because each letter group is an independent (8,4) Hamming code. Enumerating all the possibilities of error-free and correctable combinations gives:

$$\text{PNE2} = P(0\text{ errors}) + P(\text{maximum of 1 error in each letter group}) \tag{16}$$

$$\begin{aligned}
PNE2 = {} & P(0 \text{ errors in 4 groups}) \\
& + 4 \times P(0 \text{ errors in 3 groups and 1 error in 1 group}) \\
& + 6 \times P(0 \text{ errors in 2 groups and 1 error in each of 2 groups}) \\
& + 4 \times P(0 \text{ errors in 1 group and 1 error in each of 3 groups}) \\
& + P(1 \text{ error in each of 4 groups}) \qquad (17)
\end{aligned}$$

We will now introduce a shorthand notation to describe the distribution of errors in the (8,4) Hamming coding scheme, P(X in N) will describe the probability of the event that <u>precisely</u> X errors occur in <u>each</u> of N groups. For example, P(1 in 2) is the probability that precisely 1 error occurs in each of 2 groups. Thus, Eq (17) can be rewritten as:

$$\begin{aligned}
PNE2 = {} & P(0 \text{ in } 4) + 4 \times P(0 \text{ in } 3)\, P(1 \text{ in } 1) \\
& + 6 \times P(0 \text{ in } 2)\, P(1 \text{ in } 2) + 4 \times P(0 \text{ in } 1)\, P(1 \text{ in } 3) \\
& + P(1 \text{ in } 4) \qquad (18)
\end{aligned}$$

In order to calculate PNE2, some preliminary calculations must be made to determine the probabilities of 0 and 1 errors in a group. Zero errors in a group indicates all eight bits are correct. Thus,

$$P(0 \text{ in } 1) = (1 - p_e)^8 \qquad (19)$$

One error can occur in a group in $\binom{8}{1} = 8$ different ways. Then, since one bit will be in error with probability p_e ,

$$P(1 \text{ in } 1) = 8(1 - p_e)^7\, p_e \qquad (20)$$

Since the errors are independent, the probability of a word is the product of the probabilities of the four letter groups. Thus,

$P(X \text{ in } N) = [P(X \text{ in } 1)]^N$. Thus, Eq (18) can be rewritten as:

$$\begin{aligned} PNE2 = {} & [P(0 \text{ in } 1)]^4 + 4\,[P(0 \text{ in } 1)]^3\, P(1 \text{ in } 1) \\ & + 6[P(0 \text{ in } 1)]^2\, [P(1 \text{ in } 1)]^2 + 4[P(0 \text{ in } 1)]\, [P(1 \text{ in } 1)]^3 \\ & + [P(1 \text{ in } 1)]^4 \end{aligned} \tag{21}$$

Substituting Eqs (19) and (20) into Eq (21) will yield the final result. However, for reasons of simplicity, PNE2 will be left as shown in Eq (21).

Each of the (8,4) Hamming code groups detects any two bit error patterns within the group. Thus, if exactly two errors occur in at least one of the letter groups, but no more than two errors occur in any of the letter groups, there will be a detected error. However, the MIL-STD parity check bits (one for each word) will also contribute to the probability of a detected error. The contribution to PDE2 of the MIL-STD parity bit will be analyzed after the Hamming code (ignoring the parity bit) is analyzed. The (8,4) Hamming code detects any two bit errors in a single group, but if more than two errors occur in any group, the errors will be undetected.

If any of the groups contain a detected error, and none of the groups contain an undetected error, then the entire word is considered to contain a detected error. For example, if groups A and C (see Figure 1) each contain one error, group B has two errors, and group D has zero errors, the word contains a detected error even though two of the errors are correctable. Thus, the probability of a detected error (PDE) can be rewritten as the probability that exactly two errors occur in at least one of the letter groups, and that zero or one errors occur

in the other letter groups. Enumerating the possibilities and using simplified notation yields:

$$\begin{aligned}\text{Partial PDE2} = 4 \times P(2 \text{ in } 1)\ P(0 \text{ or } 1 \text{ in } 3) \\ + 6 \times P(2 \text{ in } 2)\ P(0 \text{ or } 1 \text{ in } 2) \\ + 4 \times P(2 \text{ in } 3)\ P(0 \text{ or } 1 \text{ in } 1) \\ + P(2 \text{ in } 4)\end{aligned} \tag{22}$$

where P(X or Y in N) describes the probability of the event that <u>exactly</u> X errors <u>or</u> <u>exactly</u> Y errors occur in <u>each</u> of N groups. Note that this is a partial PDE2 because the contribution of the MIL-STD parity bit has not been accounted for.

Calculating P(2 in N) for Eq (22) is relatively straightforward since $P(2 \text{ in } N) = [P(2 \text{ in } 1)]^N$. Two errors can occur in a group in $\binom{8}{2} = 28$ different ways. Then two bits will each be in error with probability p_e, while each of 6 bits will be correct with probability $1 - p_e$. Thus,

$$P(2 \text{ in } 1) = 28(1 - p_e)^6\ p_e^{\ 2} \tag{23}$$

Calculating P(0 or 1 in N) is somewhat more difficult since each N must be evaluated separately. Each case for getting 0 or 1 errors in N must be enumerated. If there are 0 errors in R, then there is 1 error in N - R and R ranges from 0 to N. Also, the number of ways of getting (0 in R) and (1 in N-R) must be evaluated. For example, (0 or 1 in 2) yields:

	N = 2	
R	N-R	number of ways
0	2	$\binom{2}{0} = 1$
1	1	$\binom{2}{1} = 2$
2	0	$\binom{2}{2} = 1$

So,

$$P(0 \text{ or } 1 \text{ in } 2) = P(0 \text{ in } 2) + 2 \times P(0 \text{ in } 1)\, P(1 \text{ in } 1) + P(1 \text{ in } 2) \tag{24}$$

Similarly,

$$P(0 \text{ or } 1 \text{ in } 3) = P(0 \text{ in } 3) + 3 \times P(0 \text{ in } 2)\, P(1 \text{ in } 1) + 3 \times P(0 \text{ in } 1)\, P(1 \text{ in } 2) + P(1 \text{ in } 3) \tag{25}$$

and,

$$P(0 \text{ or } 1 \text{ in } 1) = P(0 \text{ in } 1) + P(1 \text{ in } 1) \tag{26}$$

Of course, as previously shown, $P(X \text{ in } N) = [P(X \text{ in } 1)]^N$. Thus, Eq (24) can be rewritten as:

$$P(0 \text{ or } 1 \text{ in } 2) = [P(0 \text{ in } 1)]^2 + 2 \times P(0 \text{ in } 1)\, P(1 \text{ in } 1) + [P(1 \text{ in } 1)]^2 \tag{27}$$

and Eq (25) can be rewritten as:

$$P(0 \text{ or } 1 \text{ in } 3) = [P(0 \text{ in } 1)]^3 + 3[P(0 \text{ in } 1)]^2\, P(1 \text{ in } 1) + 3\, P(0 \text{ in } 1)\, [P(1 \text{ in } 1)]^2 + [P(1 \text{ in } 1)]^3 \tag{28}$$

Substituting Eqs (26), (27), and (28) into Eq (22) and simplifying P(2 in N) yields the partial probability of a detected error.

$$
\begin{aligned}
\text{Partial PDE2} = 4P(2\text{ in }1) & \begin{bmatrix} [P(0\text{ in }1)]^3 \\ +\ 3[P(0\text{ in }1)]^2\, P(1\text{ in }1) \\ +\ 3[P(0\text{ in }1)]\ [P(1\text{ in }1)]^2 \\ +\ [P(1\text{ in }1)]^2 \end{bmatrix} \\
+\ 6[P(2\text{ in }1)]^2 & \begin{bmatrix} [P(0\text{ in }1)]^2 \\ +\ 2P(0\text{ in }1)P(1\text{ in }1) \\ +\ [P(1\text{ in }1)]^2 \end{bmatrix} \\
+\ 4[P(2\text{ in }1)]^3 & \begin{bmatrix} P(0\text{ in }1) \\ +\ P(1\text{ in }1) \end{bmatrix} \\
+\ [P(2\text{ in }1)]^4 &
\end{aligned}
\qquad (29)
$$

Equation (29) is the probability of detected error (PDE) for the (8,4) Hamming code without using the MIL-STD parity check bit. Using the MIL-STD parity check bit will increase PDE. If an odd number of errors occurs in either of the words, the corresponding parity check bit will be set and the error will be detected. If the total number of errors in both words is odd, then an odd number of errors must occur in one of the words. Thus, any odd number of errors in either word will result in a detected error. Note, however, that if an odd number of errors occurs in both words, the error will be detected but the total number of errors is even. This last case would be difficult to calculate and would not significantly increase PDE. Therefore, adding only odd errors to PDE results in a lower bound for PDE.

If the total number of errors is 3, 5, or 7, then certain error patterns totaling 3, 5, or 7 errors have already been included in Eq (29). Thus, these error patterns should be subtracted from the total so they are not counted twice. Also, one case of a three bit error pattern and all one bit errors result in a correctable error. These should not be counted since they do not result in a detected error. The probability of all odd numbers of errors greater than or equal to three is given by:

$$P(\text{odd}) = \sum_{\substack{n=3,5,7,\\ \ldots,31}} \binom{32}{n} (1 - p_e)^{32-n}\, p_e^{\,n} \tag{30}$$

If this is added to Eq (29), certain error patterns would be counted twice. These patterns must be subtracted from the total. The error patterns that are counted twice are:

3 bit errors: 2 in 1 group, 1 in 1 group, 0 in 2 groups

5 bit errors: 2 in 1 group, 1 in 3 groups

2 in 2 groups, 1 in 1 group, 0 in 1 group

7 bit errors: 2 in 3 groups, 1 in 1 group

The probability of these cases is given by

3 bit errors: $4P(2 \text{ in } 1) \times 3P(1 \text{ in } 1)[P(0 \text{ in } 1)]^2$ (31a)

5 bit errors: $4P(2 \text{ in } 1)[P(1 \text{ in } 1)]^3$ (31b)

$6[P(2 \text{ in } 1)]^2 \times 2P(1 \text{ in } 1)\, P(0 \text{ in } 1)$ (31c)

7 bit errors: $4[P(2 \text{ in } 1)]^3\, P(1 \text{ in } 1)$ (31d)

The three bit error pattern that is correctable is 1 error in 3 groups and 0 errors in the remaining group. Its probability is given by

$$4P(0 \text{ in } 1)\ [P(1 \text{ in } 1)]^3 \tag{32}$$

Thus, the total probability of a detected error is given by the sum of Eqs (29) and (30) minus Eqs (31a-d) and (32) as shown below:

$$\begin{aligned}
\text{PDE2} = & \sum_{\substack{n=3,5,7,\\ \ldots,31}} \binom{32}{n} (1 - p_e)^{32-n}\, p_e^{\,n} \\
& + 4P(2 \text{ in } 1) \left[\begin{aligned} & [P(0 \text{ in } 1)]^3 \\ & + 3P(0 \text{ in } 1)\ [P(1 \text{ in } 1)]^2 \end{aligned} \right] \\
& + 6[P(2 \text{ in } 1)]^2 \left[\begin{aligned} & [P(0 \text{ in } 1)]^2 \\ & + [P(1 \text{ in } 1)]^2 \end{aligned} \right] \\
& + 4[P(2 \text{ in } 1)]^3\, P(0 \text{ in } 1) \\
& + [P(2 \text{ in } 1)]^4 \\
& - 4P(0 \text{ in } 1)\ [P(1 \text{ in } 1)]^3
\end{aligned} \tag{33}$$

PNE2, PDE2, and PUE2 are mutually exclusive and they partition the possible events. Therefore,

$$\text{PNE2} + \text{PDE2} + \text{PUE2} = 1 \tag{34}$$

PNE2 and PDE2 have already been calculated (Eqs (21) and (33) respectively); therefore, PUE2 can be calculated by subtracting these values from 1. Therefore,

$$PUE2 = 1 - PDE2 - PNE2 \tag{35}$$

This completes the evaluation of word error rates for the (8,4) Hamming code. The probability of a correct word (PNE2) is given in Eq (21). The probability of a detected error (PDE2) is given in Eq (33). The probability of an undetected error is given in Eq (35).

BCH Codes

The Mississippi State University (MSU) study (Ref 4) employs BCH codes to accomplish the desired error protection. The MSU study uses the first five bits of the first data word following the command word as an additional subaddress field for the command word. This allows the original MIL-STD-1553B subaddress field (bits 10-14) of the command word to be used to tell the remote terminal that additional error protection has been employed. Thus, there are 21 information-containing bits in the command word-first data word pair. These two words are encoded using a (31,21,2) BCH code format as shown in Figure 3. The ten parity check bits immediately follow the five information bits in the first data word and one bit is unused as shown in Figure 3.

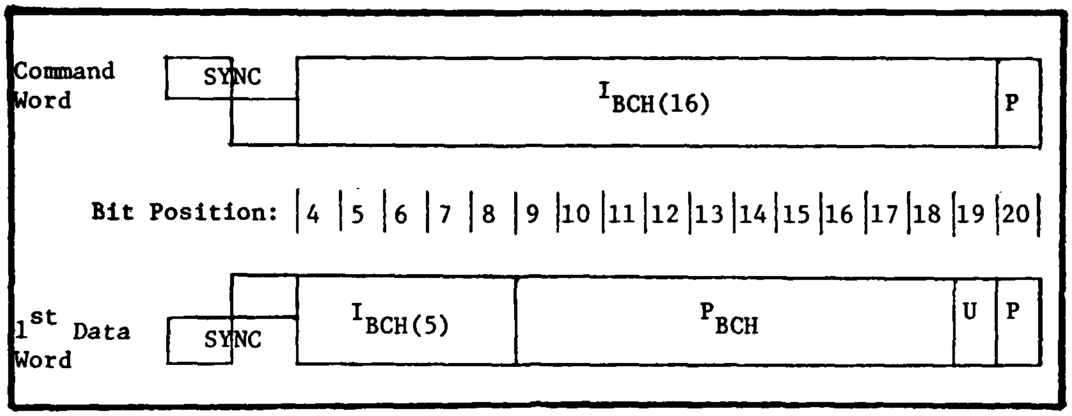


Figure 3. Command Word - Data Word Pair Using the (31,21,2) BCH Code

where: $I_{BCH(16)}$ = 16 of 21 information bits of the (31,21,2) BCH Code

$I_{BCH(5)}$ = 5 of 21 information bits of the (31,21,2) BCH Code

P_{BCH} = 10 parity bits of the (31,21,2) BCH Code

U = unused bit

P = MIL-STD-1553B parity bit

SYNC = three bit synchronization signal

The information in this coding scheme is encoded in a (31,16,3) BCH code format which requires two MIL-STD-1553B words for each 16 bits of information. The first data word contains the 16 bits of information, while the second data word contains the 15 parity check digits, as shown in Figure 4.

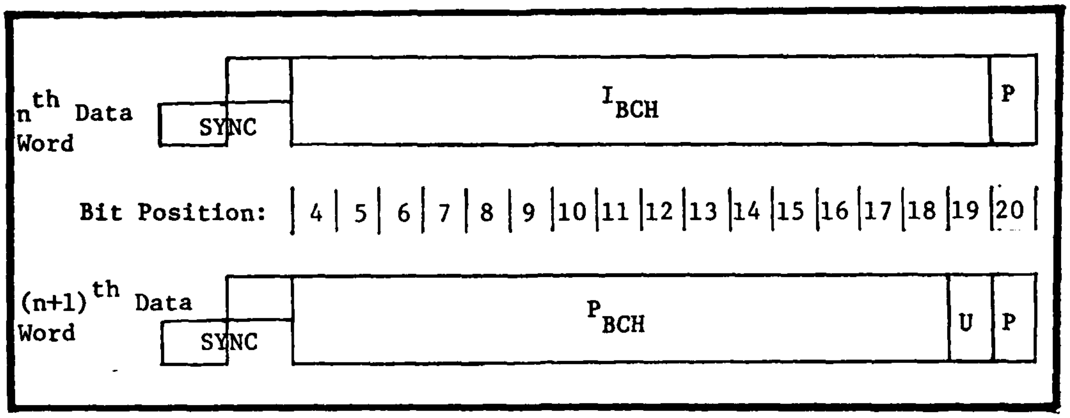


Figure 4. Data Word - Data Word Pair Using the (31,16,3) BCH Code

where: I_{BCH} = 16 information bits of the (31,16,3) BCH code

P_{BCH} = 15 parity bits of the (31,16,3) BCH code

U = unused bit

P = MIL-STD-1553B parity bit

SYNC = three bit synchronization signal

The MIL-STD maximum total message consists of 1 command word and 32 data words. In the BCH scheme, the first data word is used to protect the command word; therefore, there are 31 data words remaining to transfer information. However, since the data coding scheme requires pairs of data words, there are only 15 complete pairs and the last data word remains unused. Each of the 15 pairs of data words has 16 information bits; thus, the maximum message has 16 x 15 = 240 bits of information. This is only 47% of the number of bits in the maximum length message with no error encoding.

This BCH coding scheme can be used in any of three ways. In a forward error correcting (FEC) configuration, the codes are used only to correct certain errors. In a pure ARQ configuration, the codes are used only to detect errors. In a hybrid ARQ configuration, the codes will correct certain errors and detect certain other errors. The effects of these configurations on the entire system will be shown later. In this section, the word error rates for each of the possible configurations will be calculated. These calculations verify the results presented in the Mississippi State University Paper.

Error Detection Configuration.

Command word - (31,21,2) BCH code. Since in this mode this code will not be used to correct any errors, the probability that the correct action is taken (PNE2) is the probability that all bits are received correctly. Again, the probability of a single bit error is p_e and there are 31 bits that must be received correctly. Thus,

$$PNE2 = (1 - p_e)^{31} \tag{36}$$

This code has a minimum distance of five so it can detect up to $d_{min} - 1 = 4$ errors . Also, as discussed in the section on Hamming codes, the MIL-STD parity bit will independently detect any odd errors. Thus, all errors of 1, 2, 3, and 4 bits and odd errors between 5 bits and 31 bits will be detected.

$$PDE2 = \sum_{\substack{n=1,2,3,4,5,\\7,\ldots,31}} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{37}$$

The probability of an undetected error (PUE2), PNE2, and PDE2 partition all possible events. Therefore, PUE2 can be found easily as

$$PUE2 = 1 - PNE2 - PDE2 \tag{38}$$

Data word - (31,16,3) BCH code. This analysis is very similar to the analysis for the (31,21,2) BCH code. The only difference is the (31,16,3) BCH code has a minimum distance of seven; therefore, it can detect up to $d_{min} - 1 = 6$ errors . Thus, the word error rates for the (31,16,3) BCH code can be written as:

$$PNE2 = (1 - p_e)^{31} \tag{39}$$

$$PDE2 = \sum_{\substack{n=1,2,3,4,5,6, \\ 7,9,\ldots,31}} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{40}$$

$$PUE2 = 1 - PNE2 - PDE2 \tag{41}$$

Error Correction Only.

Command word - (31,21,2) BCH code. This code will correct up to two bit errors. Therefore, the probability that the correct action is taken (PNE2) is the probability of 0, 1, or 2 errors.

$$PNE2 = \sum_{n=0}^{2} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{42}$$

Since this code is only used for error correction, the only detected errors will be detected by the MIL-STD parity bit. Thus, the probability of a detected error (PDE2) will be the probability of any odd errors greater than 2 and less than or equal to 31.

$$PDE2 = \sum_{\substack{n=3,5,7,\\ \ldots,31}} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{43}$$

and

$$PUE2 = 1 - PNE2 - PDE2 \tag{44}$$

<u>Data words - (31,16,3) BCH code</u>. This uses the same analysis as the (31,21,2) BCH code, but this code will correct up to three errors. Thus, the word error rates for the (31,16,3) BCH code are:

$$PNE2 = \sum_{n=0}^{3} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{45}$$

$$PDE2 = \sum_{\substack{n=5,7,9,\\ \ldots,31}} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{46}$$

$$PUE2 = 1 - PNE2 - PUE2 \tag{47}$$

<u>Hybrid - Error Correction and Detection</u>. The hybrid scheme combines the detection and correction capabilities of the BCH code in one scheme. This scheme uses the full error correction capability of the code, but does not sacrifice any of the detection capability.

<u>Command word - (31,21,2) BCH code</u>. Since the full error correction capability of the code is retained, the probability of correct action (PNE2) is the same as in Eq (42).

$$PNE2 = \sum_{n=0}^{2} \binom{31}{n} (1 - p_e)^{31-n} \, p_e^{\,n} \tag{48}$$

This scheme does not sacrifice any detection capabilities so it will still detect up to four errors. However, 1 or 2 errors result in the correct action, so

$$PDE2 = \sum_{\substack{n=3,4,5,7,\\ \dots,31}} \binom{31}{n} (1 - p_e)^{31-n} p_e^{\,n} \tag{49}$$

Also,

$$PUE2 = 1 - PNE2 - PDE2 \tag{50}$$

<u>Data word - (31,16,3) BCH code</u>. Again, the (31,16,3) BCH code uses the same analysis as the (31,21,2) BCH code; therefore,

$$PNE2 = \sum_{n=0}^{3} \binom{31}{n} (1 - p_e)^{31-n} p_e^{\,n} \tag{51}$$

$$PDE2 = \sum_{\substack{n=4,5,6,7,\\ 9,\dots,31}} \binom{31}{n} (1 - p_e)^{31-n} p_e^{\,n} \tag{52}$$

$$PUE2 = 1 - PNE2 - PDE2 \tag{53}$$

<u>Block Error Rates</u>

The analyses in the following chapters require block error rates to produce meaningful results. Therefore, the word error rates already calculated in this chapter must be converted to block error rates. This conversion requires knowledge of the MIL-STD-1553B message formats (see Appendix A). According to the standard, message lengths, and thereby, block lengths may vary. There is no experimental data to estimate the average message length. Therefore, the upper and lower

bounds of the message length are used to bound the block error rates. The block error rates for the various coding schemes are given in Appendix C.

Block Detected Error. A message in MIL-STD-1553B consists of a command word, 1-32 data words, and 1 status word. The status word will not affect this analysis so it will be ignored. Both the Hamming and BCH coding schemes encode the command word and data words differently. Therefore, a message can be divided into two groups. Group 1 contains the command word and any additional parity check bits for the command word. Group 2 contains all the data words and their associated parity check bits. A message is detected in error if there is a detected error in group 1, group 2, or both group 1 and group 2. The Venn diagram for this situation is shown below (Figure 5). Thus, the probability of a detected block error is the sum of C, D, and E from Figure 5. As shown in A and B from Figure 5, a detected error in a group is denoted as $d_{\text{group number}}$. Thus, the probability of a block detected error, PBDE is

$$PBDE = Pr(d_1 \cap \bar{d}_2) + Pr(d_2 \cap \bar{d}_1) + Pr(d_1 \cap d_2) \tag{54}$$

The terms in this equation are the areas: D, E, and C (from Figure 5) respectively. This equation is correct because areas C, D, and E partition the entire detected error space. It can be simplified further because the errors are independent. Thus,

$$PBDE = Pr(d_1)Pr(\bar{d}_2) + Pr(d_2)Pr(\bar{d}_1) + Pr(d_1)Pr(d_2) \tag{55}$$

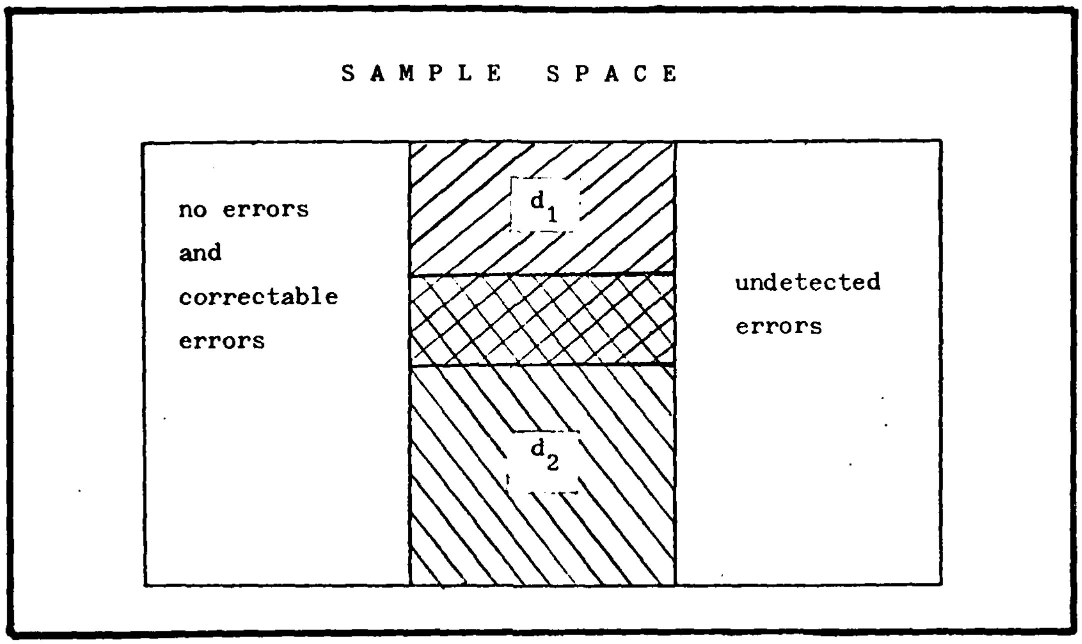
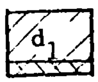


Figure 5. Venn Diagram for the Probability of a Block Detected Error

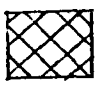
where:

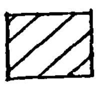
A. 

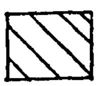
: detected error in group 1 = d_1

B. 

: detected error in group 2 = d_2

C.  : detected error in both group 1 and group 2

D.  : detected error in group 1, but not in group 2

E.  : detected error in group 2, but not in group 1

Simplifying this yields

$$PBDE = Pr(d_1)[Pr(\overline{d}_2) + Pr(d_2)] + Pr(d_2)Pr(\overline{d}_1)$$

but, $$Pr(\overline{d}_1) = 1 - Pr(d_1)$$

$$PBDE = Pr(d_1) + Pr(d_2) - Pr(d_1)Pr(d_2) \tag{56}$$

This can be rewritten as

$$PBDE = Pr(d_1) + [1 - Pr(d_1)]Pr(d_2) \tag{57}$$

But $Pr(d_2)$ can be expressed as

$$Pr(d_2) = Pr(\geq 1 \text{ detected errors occur in group } 2)$$

$$= \sum_{n=1}^{NDW} \binom{NDW}{n} PDE_{DW}^{n} (1 - PDE_{DW})^{NDW-n} \tag{58}$$

where:

PDE_{DW} = probability of a detected error in a single data word

NDW = number of data words

Clearly then,

$$Pr(d_2) = 1 - (1 - PDE_{DW})^{NDW} \tag{59}$$

Substituting Eq (59) into Eq (57) yields

$$PBDE = Pr(d_1) + [1 - Pr(d_1)]\ [1 - (1 - PDE_{DW})^{NDW}] \tag{60}$$

This can be further simplified to yield

$$PBDE = Pr(d_1) + [1 - (1 - PDE_{DW})^{NDW}] - Pr(d_1)$$
$$+ Pr(d_1) \; [(1 - PDE_{DW})^{NDW}]$$
$$= 1 - (1 - PDE_{DW})^{NDW} + Pr(d_1) \; (1 - PDE_{DW})^{NDW}$$
$$= 1 + [Pr(d_1) - 1] \; [(1 - PDE_{DW})^{NDW}] \tag{61}$$

But since group 1 contains only the command word, a detected error in group 1 is a detected error in the command word, i.e., $Pr(d_1) = PDE_{CW}$. Substituting this into Eq (61) yields

$$PBDE = 1 + [PDE_{CW} - 1] \; [(1 - PDE_{DW})^{NDW}] \tag{62}$$

<u>Block</u> <u>With</u> <u>No</u> <u>Error</u>. An entire message can be received correctly only if all the words in the message are received correctly. Therefore, PBNE = probability (no errors occur in any words in the block or all errors are corrected). A message will again be divided into command words and data words. The only combination that will result in a correctly received block is no errors in group 1 (command words) and no errors in group 2 (data words). This is shown in the Venn diagram in Figure 6. Thus, as shown in Figure 6,

$$PBNE = Pr(c_1 \cap c_2) \tag{63}$$

But since c_1 and c_2 are independent,

$$PBNE = Pr(c_1)Pr(c_2) \tag{64}$$

Since there is only one command word (or one command word-data word pair) in any message,

$$Pr(c_1) = PNE_{CW} \tag{65}$$

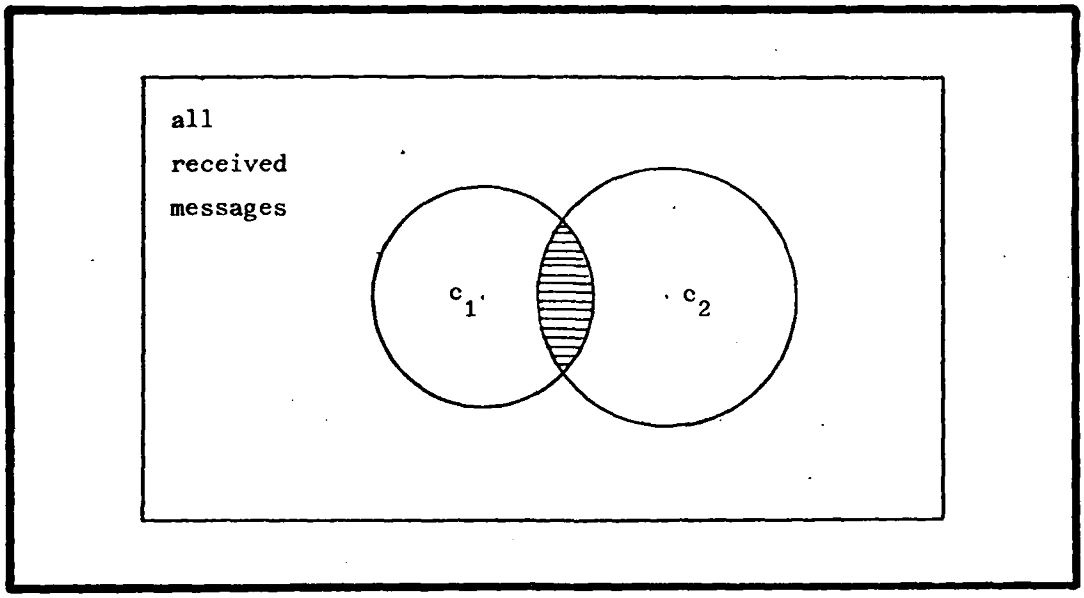
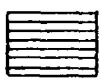


Figure 6. Venn Diagram for the Probability of a Correctly Received Block

where: c_1 = correctable errors in group 1

c_2 = correctable errors in group 2

 = correctable errors in both group 1 and group 2

$Pr(c_2)$ denotes that every data word must be decoded correctly. Let NDW = number of data words , then

$$Pr(c_2) = Pr(DW1_c \cap DW2_c \cap \ldots \cap DW(NDW)_c) \tag{66}$$

but all errors are independent and all data words have the same probability of being correct, PNE_{DW}. Thus,

$$Pr(c_2) = Pr(DW1_c)Pr(DW2_c)\ldots Pr(DW(NDW)_c)$$

$$= (PNE_{DW})^{NDW} \quad (67)$$

Substituting Eqs (65) and (67) into (64) yields

$$PBNE = PNE_{CW}(PNE_{DW})^{NDW} \quad (68)$$

Block Undetected Error. Since the block error probabilities are mutually exclusive,

$$PBNE + PBDE + PBUE = 1 \quad (69)$$

where PBUE = probability of a block undetected error . PBNE and PBDE are already known; therefore, PBUE can be found simply.

$$PBUE = 1 - PBNE - PBUE \quad (70)$$

The equations for calculating the block error probabilities for any of the coding schemes are given on the following pages. The numerical results of these calculations (for a range of bit error probabilities) are given in Appendix C. These block error probabilities will be used in the following chapters to calculate throughput and overall system error for various transmission schemes.

In general, the equations for calculating the block error rates given the word error rates are

$$PBDE = 1 + [PDE_{CW} - 1]\ [(1 - PDE_{DW})^{NDW}] \quad (62)$$

$$PBNE = PNE_{CW}(PNE_{DW})^{NDW} \quad (68)$$

$$PBUE = 1 - PBNE - PBDE \tag{70}$$

<u>MIL-STD-1553B Without Additional Error Protection</u>. For MIL-STD-1553B without additional error protection, the word error rates are the same for both command words and data words. The block error rates for this case (denoted by subscript M-S) are then:

$$PBDE_{M-S} = 1 + [(1 - PDE)^{NDW}]\ (PDE - 1) \tag{71}$$

$$PBNE_{M-S} = PNE^{NDW+1} \tag{72}$$

$$PBUE_{M-S} = 1 - PBNE_{M-S} - PBDE_{M-S} \tag{73}$$

where $1 \leq NDW \leq 32$. Both the number of information-containing bits and the total number of bits in a message are necessary for the analysis in the following chapters. The information-containing bits are the bits in the data word that contain information for the destination. Without additional error protection, MIL-STD data words contain 16 information bits. Therefore, the number of information bits, k_{M-S} is given by

$$k_{M-S} = 16 \times NDW \tag{74}$$

The total number of bits, n, in a message includes all information bits, any parity bits, and any synchronization bits. Since each word in the MIL-STD format contains a total of 20 bits. The total number of bits, n_{M-S} in a message is

$$n_{M-S} = 20(NDW + 1) \tag{75}$$

Hamming Codes. The block error rates for Hamming codes fit the general case, except that the command word error rate is for two MIL-STD words. The block error rates (denoted by subscript H) are

$$PBDE_H = 1 + [(1 - PDE_{DW})^{NDW}] \ (PDE2_{CW} - 1) \tag{76}$$

$$PBNE_H = PNE2_{CW}(PNE_{DW})^{NDW} \tag{77}$$

$$PBUE_H = 1 - PBNE_H - PBDE_H \tag{78}$$

where $1 \leq NDW \leq 31$. Each data word contains 11 information bits and 5 parity bits (see Figure 2). Thus, the number of information bits, k_H , is

$$k_H = 11 \times NDW \tag{79}$$

The total number of bits in the message is 20 times the number of words in the message. There are NDW data words in a message and there are two command words in every message. Then the total number of bits in a message is

$$n_H = 20(NDW + 2) \tag{80}$$

BCH Codes. In the BCH coding scheme, both the command word and the data word error rates are for two MIL-STD words. Thus, the data word error rates need only be counted once for each pair of MIL-STD data words. The block error rates for the BCH codes (denoted by subscript BCH) are

$$PBDE_{BCH} = 1 + (1 - PDE2_{DW})^{\frac{NDW}{2}} \ (PDE2_{CW} - 1) \tag{81}$$

$$PBNE_{BCH} = PNE2_{CW}\ (PNE2_{DW})^{\frac{NDW}{2}} \tag{82}$$

$$PBUE_{BCH} = 1 - PBNE_{BCH} - PBDE_{BCH} \tag{83}$$

where $2 \leq NDW \leq 30$ and NDW is even. Each data word pair contains 16 information bits and 15 parity bits (see Figure 4). Then the number of information bits, k_{BCH}, is

$$k_{BCH} = 16 \times \frac{NDW}{2} = 8NDW \tag{84}$$

As with the Hamming code, there are NDW data words in a message and two command words in a message. Then

$$n_{BCH} = 20(NDW + 2) \tag{85}$$

The results given in Eqs (71) through (85) will be used in the following chapters to evaluate the throughput and overall probability of error for various transmission schemes.

III. Analysis of Stop-and-Wait ARQ Transmission Scheme

Introduction

This chapter deals with the Automatic Repeat Request (ARQ) Transmission scheme employed in the stop-and-wait mode. This scheme will be modeled and analyzed with both a perfect and an imperfect return channel. An ARQ scheme requires an error detecting channel code. As such, only one of the proposed coding schemes, the BCH codes used in their error detecting mode, will fit this model. Thus, the command word-data word pair will be encoded using the BCH (31,21,2) format, while the data word-data word pairs will be encoded using the BCH (31,16,3) format. The word error rates for these codes are given in Appendix B and the resulting block error probabilities are found in Appendix C.

The acknowledgement (ACK/NACK) signal for the ARQ transmission scheme is embedded in the status word. Because of the constraints of MIL-STD-1553B, only one bit can be used as an ACK/NACK signal. The message error bit at bit position nine in the status word will be used as the ACK/NACK signal. A logic zero indicates an ACK and a logic one indicates a NACK. Since the system operates in the command/response mode, there will always be a status word and hence an acknowledgement signal transmitted (see Appendix A).

Analysis For A Perfect Return Channel (Ref 1:136-137)

With a perfect return channel, the acknowledgement signal will always be received correctly by the bus controller. If an error is detected in a message, then a retransmission is guaranteed. Likewise, if no error is detected in a message, there will be no retransmission.

Thus, the system can be analyzed in terms of the message (block) error rates. The block error rates have been calculated in the last chapter.

Probability of Error. The probability of any error in a block equals the probability of an undetected error in a block plus the probability of a detected error in a block as shown in Eq (86).

$$P_E = P_d + P_u \tag{86}$$

where:

P_E = probability of any error in a block

P_d = probability of a detected error in a block

P_u = probability of an undetected error in a block

Each message will have one of three mutually exclusive outcomes:

1. The message will be received correctly.
2. An error will be detected and a NACK will be sent.
3. An undetected error will occur.

Since P_E is the probability of any error in the block, the probability that the message will be received correctly is $1 - P_E$. The probabilities of a detected and an undetected error are defined (Eq (86)) respectively as P_d and P_u. Note that the sum of the probabilities of the three outcomes $(1 - P_E + P_d + P_u)$ equals 1 as expected.

Since this model has a perfect return channel, the ACK/NACK signal will always be correctly interpreted. One of two possible outcomes will always be the final transmission of a given message. The two outcomes are:

1. The message is received correctly.
2. The message is never received correctly.

The probabilities for these events are defined as P_C and P_U, respectively. Since these events partition the possible final outcomes, $P_C + P_U = 1$. Given the definition, P_C can be expressed as the probability that the message is received correctly given that the message was the final transmission. This can be expressed by conditional probability (Ref 8:35) as:

$$P_C = \Pr(\text{Correct/Final Event}) = \frac{\Pr(\text{Correct, Final Event})}{\Pr(\text{Final Event})} \tag{87}$$

However, the final transmission can only have two outcomes, and these two outcomes partition the sample space. Therefore, the probability of the final event is:

$$\begin{aligned}\Pr(\text{Final Event}) = {} & \Pr(\text{message correct, Final Event}) \\ & + \Pr(\text{undetected error, Final Event})\end{aligned} \tag{88}$$

Thus, Eq (87) can be written as:

$$P_C = \frac{\Pr(\text{Correct, Final Event})}{\Pr(\text{Correct, Final Event}) + \Pr(\text{Undetected Error, Final Event})} \tag{89}$$

With this transmission scheme, if the message is correct or an error is undetected, then the message is accepted as the final transmission. Therefore, any time the message is correct or an undetected error occurs in the message, the final transmission has occurred regardless of which transmission occurred. It follows that:

$$\Pr(\text{Correct, Final Event}) = \Pr(\text{Correct, Any Event}) \tag{90}$$

Pr(Undetected Error, Final Event)

$$= \Pr(\text{Undetected Error, Any Event}) \tag{91}$$

Now, using

$$\Pr(\text{Correct, Any Event}) = 1 - P_E \tag{92}$$

$$\Pr(\text{Undetected Error, Any Event}) = P_u \tag{93}$$

in Eq (89) yields

$$P_C = \frac{1 - P_E}{1 - P_E + P_u} \tag{94}$$

Similarly, the probability that the message is received incorrectly given that the final transmission has occurred is:

$$P_U = \Pr(\text{Undetected Error/Final Event})$$

$$= \frac{\Pr(\text{Undetected Error, Final Event})}{\Pr(\text{Final Event})} \tag{95}$$

or

$$P_U = \frac{P_u}{1 - P_E + P_u} \tag{96}$$

Using $P_E = P_d + P_u$, Eq (94) can be written as

$$P_C = 1 - \frac{P_u}{1 - P_d} \tag{97}$$

while P_U (Eq (96)) can be expressed as

$$P_U = \frac{P_u}{1 - P_d} \tag{98}$$

Thus, as expected, $P_C + P_U = 1$, where P_U is the probability that a message will never be received correctly which is the overall probability of error, ρ .

<u>Throughput</u>. A second performance criterion is throughput. Throughput is the ratio of information bits to the total number of bits required to complete the data transfer. A retransmitted message only adds to the total number of bits since it contains no new information. The number of bits in a single transmission includes all the bits in the message, the wait time (in bits) before the acknowledgement signal is received, and the length of the acknowledgement signal. Thus, the total number of bits equals the expected number of transmissions multiplied by the number of bits in one transmission. Thus, the throughput can be expressed as

$$R = \frac{k}{(n + \tau + s)E} \tag{99}$$

where:

R = throughput

k = the number of information bits

n = the number of bits in the message

τ = the wait time (in bits) for the acknowledgement signal

s = the number of bits in the acknowledgement signal

E = the expected number of transmissions

The number of information bits, k, is a function of the number of data words in a message. The number of bits in the message, n, is also dependent on the number of data words in the message. According

to MIL-STD-1553B, the response time for any terminal shall be between 4.0 and 12.0 μsec. Assuming the worst case and noting that the channel rate is 1 bit/μsec ; the wait time is $\tau = 12$ bits for any coding scheme. The acknowledgement signal must be embedded in the status word. Thus, the entire status word contributes to the total number of bits and $s = 20$ in all cases.

The calculation of E is somewhat more difficult. Let Δ be the number of transmissions until the message is accepted (either correctly or with an undetected error). Then

$$\Pr(\Delta=1) = \Pr(\text{message accepted on } 1^{st} \text{ transmission}) = 1-P_d \tag{100a}$$

$$\Pr(\Delta=2) = \Pr\begin{pmatrix}\text{detected error on } 1^{st} \text{ transmission} \\ \text{message accepted on } 2^{nd} \text{ transmission}\end{pmatrix} = P_d(1-P_d) \tag{100b}$$

$$\Pr(\Delta=3) = \Pr\begin{pmatrix}\text{detected error on } 1^{st} \text{ transmission} \\ \text{message accepted on } 3^{rd} \text{ transmission}\end{pmatrix} = P_d^{\,2}(1-P_d) \tag{100c}$$

$$\vdots \qquad\qquad\qquad \vdots \qquad\qquad\qquad \vdots$$

$$\Pr(\ =L) = \Pr\begin{pmatrix}\text{detected error on } 1^{st}, 2^{nd}, \ldots, (L-1)^{st} \\ \text{message accepted on } L^{th} \text{ transmission}\end{pmatrix}\text{transmission}$$

$$= P_d^{\,(L-1)}\ (1-P_d) \tag{100d}$$

Then since E is the expected number of transmissions, E is the expected value of Δ. For a discrete random variable (Ref 8:119)

$$E(X) = \sum_{i=1}^{\infty} x_i \Pr(x_i) \tag{101}$$

Thus

$$E = E(\Delta) = (1 - P_d) + 2\,P_d(1 - P_d) + 3\,P_d(1 - P_d) + \ldots$$

$$= (1 - P_d) \sum_{L=1}^{\infty} L\,P_d^{\,L-1} \tag{102}$$

But

$$\sum_{L=1}^{\infty} L\,P_d^{\,L-1} = \frac{d}{d\,P_d} \sum_{L=1}^{\infty} P_d^{\,L} \tag{103}$$

Then

$$\sum_{L=1}^{\infty} P_d^{\,L} = \frac{1}{1 - P_d} \qquad \text{since} \qquad 0 < P_d < 1 \tag{104}$$

Substituting Eqs (103) and (104) into (102) yields

$$E = (1 - P_d) \frac{d}{d\,P_d} \left(\frac{1}{1 - P_d} \right)$$

$$= \frac{1}{1 - P_d} \tag{105}$$

Thus, throughput can be written as

$$R = \frac{k(1 - P_d)}{n + \tau + s} \tag{106}$$

<u>Analysis For An Imperfect Return Channel</u>

This analysis is more realistic than the perfect return channel analysis because it accounts for the possibility of an error in the acknowledgement signal. As previously mentioned, the ACK/NACK signal is embedded in the status word. The MIL-STD status word has a

single parity bit which detects any odd errors. But if an error is detected there is no way of determining which bit(s) contain(s) the error(s). Now, we cannot be sure the ACK/NACK signal is correct; therefore, when any error is detected in the status word, the acknowledgement signal will be interpreted as a NACK. An undetected error occurs whenever there is an even number of errors in the status word. In this case, the acknowledgement signal may be correct or incorrect. If the acknowledgement signal is incorrect, an undetected retransmission error occurs. If the acknowledgement signal is correct, the correct retransmission action will take place even though an undetected error has occurred in the status word. The bit error rates for the status word are assumed to be the same as the bit error rates for the command and data words since the same data bus is used to return the status word to the bus controller. Thus, the probability that the acknowledgement signal bit is incorrect is p_e. The probability of an undetected acknowledgement signal error is

$$P'_u = \sum_{\substack{n=1,3,5,\\ \ldots,15}} \binom{16}{n} p_e^{\,n+1} (1 - p_e)^{16-n} \tag{107}$$

Any detected errors in the status word will be interpreted as NACK signals regardless of where the error(s) occur. Since any odd number of errors causes a detected error, the probability of a detected error is

$$P'_d = \sum_{\substack{n=1,3,5,\\ \ldots,17}} \binom{17}{n} p_e^{\,n} (1 - p_e)^{17-n} \tag{108}$$

The probability of any error in the acknowledgement signal is the probability of a detected error plus the probability of an undetected error as shown below:

$$P'_E = P'_d + P'_u \tag{109}$$

<u>Probability of Error</u>. As in the perfect return channel analysis, the probability of any error in a block equals the probability of an undetected error in a block plus the probability of a detected error in a block.

$$P_E = P_d + P_u \tag{110}$$

In this analysis, as in Benice and Frey's paper (Ref 1:137), it is considered that there is no penalty for retransmission of a message that has already been received correctly. If there is a penalty associated with these retransmissions, additional analysis must be done to include these retransmissions.

Since there is no penalty for retransmission of a correctly received message, there are five mutually exclusive outcomes of each transmission:

1. The message will be received correctly.

2. The message will contain a detected error and retransmission will occur.

3. The message will contain a detected error, but no retransmission will occur.

4. The message will contain an undetected error and no retransmission will occur.

5. The message will contain an undetected error, but retransmission will occur.

The probability of each of the five events is determined as follows:

1. The probability of an error in the block is P_E. Thus the probability of a correct message is $1 - P_E$.

2. A detected error in the message occurs with probability P_d. The return message is interpreted as a NACK if it is received correctly or an error is detected. The probability of these is $1 - P'_E + P'_d = 1 - P'_u$. Thus, the probability of a detected error and retransmission is $Pd(1 - P'_u)$.

3. Similar to the last case, except the return is interpreted as an ACK with probability P'_u . The probability of a detected error with no retransmission is $P_d P'_u$.

4. An undetected error in the message occurs with probability P_u. The return message will be interpreted as an ACK only if the acknowledgement signal is correct. Thus an undetected error with no retransmission occurs with probability $P_u(1 - P'_E)$.

5. Similarly, an undetected error with retransmission occurs with probability $P_u P'_E$.

Note that the sum of the probabilities of these five events is 1.

Because of the possibility of an error in the acknowledgement signal, there are three possible outcomes of the final transmission of a given message.

A. The message is received correctly.

B. The message is never received correctly because an error was detected but no retransmission occurred.

C. The message is never received correctly because an undetected error occurred and there is no retransmission.

The probabilities for these three events are defined as P_C, P_D, and P_U respectively. As in the perfect return channel analysis, the probability of each of the three events can be found by conditional probabilities. Thus, P_C is the probability that the message is received correctly given that the message was the final transmission,

$$P_C = \Pr(\text{Correct/Final Event}) = \frac{\Pr(\text{Correct, Final Event})}{\Pr(\text{Final Event})} \tag{111}$$

The final event can only have one of three possible outcomes, thus:

$$\begin{aligned} \Pr(\text{Final Event}) = {} & \Pr(\text{message correct, Final Event}) \\ & + \Pr(\text{detected error}_{(\text{No RTR})}, \text{Final Event}) \\ & + \Pr(\text{undetected error}_{(\text{No RTR})}, \text{Final Event}) \end{aligned} \tag{112}$$

where RTR indicates retransmission.

But if any of the three events (A, B, or C) occur on a given transmission, it will be the final transmission regardless of the number of previous transmissions (if any). It follows that:

$$\Pr(\text{Correct, Final Event}) = \Pr(\text{Correct, Any Event}) = 1 - P_E \tag{113}$$

$$\begin{aligned} & \Pr(\text{Detected Error}_{(\text{No RTR})}, \text{Final Event}) \\ & \quad = \Pr(\text{Detected Error}_{(\text{No RTR})}, \text{Any Event}) \\ & \quad = P_d P_u' \end{aligned} \tag{114}$$

$$\Pr(\text{Undetected Error}_{(\text{No RTR})}\ , \text{Final Event})$$

$$= \Pr(\text{Undetected Error}_{(\text{No RTR})}\ , \text{Any Event})$$

$$= P_u(1 - P_E') \tag{115}$$

Now Eq (111) can be written as

$$P_C = \frac{1 - P_E}{1 - P_E + P_d P_u' + P_u(1 - P_E')} \tag{116}$$

Similarly

$$P_D = \frac{P_d P_u'}{1 - P_E + P_d P_u' + P_u(1 - P_E')} \tag{117}$$

and

$$P_U = \frac{P_u(1 - P_E')}{1 - P_E + P_d P_u' + P_u(1 - P_E')} \tag{118}$$

The message is never received correctly only if its final transmission is event B (detected error with no retransmission) or event C (undetected error with no retransmission). The probability of error for the system, ρ , is the probability of events B and C.

$$\rho = P_D + P_U = 1 - P_C \tag{119}$$

or, using Eq (116)

$$\rho = 1 - \frac{1 - P_E}{1 - P_E + P_d P_u' + P_u(1 - P_E')} \tag{120}$$

<u>Throughput</u>. The basic equation for throughput has been given as

$$R = \frac{k}{(n + \tau + s)E} \tag{99}$$

The addition of the imperfect return channel to the analysis only changes E, the expected number of transmissions. Again, let Δ be the number of transmissions until the message is accepted and not repeated. Then

$$\begin{aligned} Pr(\Delta=1) &= Pr(\text{message is accepted on } 1^{st} \text{ try}) \\ &= [(1 - P_E)(1 - P_E') + P_d P_u' + P_u(1 - P_E')] \\ &= [(1 - P_d)(1 - P_E') + P_d P_u'] \\ &\triangleq 1 - F \end{aligned} \tag{121}$$

and

$$\begin{aligned} Pr(\Delta=2) &= [(1 - P_E)P_E' + P_d(1 - P_u') + P_u P_E'](1 - F) \\ &= [(1 - P_d)P_E' + P_d(1 - P_u')](1 - F) \end{aligned} \tag{122}$$

Note that

$$(1 - P_d)P_E' + P_d(1 - P_u') + \underbrace{(1 - P_d)(1 - P_E') + P_d P_u'}_{1 - F} = 1$$

Now Eq (122) can be expressed as

$$Pr(\Delta=2) = F(1 - F) \tag{123}$$

and the general case is

$$Pr(\Delta=L) = F^{L-1}(1 - F) \tag{124}$$

The expected number of transmissions is now

$$E = E(\Delta) = \sum_{L=1}^{\infty} L\, F^{L-1} (1 - F)$$

$$= (1 - F) \frac{d}{dF} \sum_{L=1}^{\infty} F^{L}$$

$$= (1 - F) \frac{d}{dF} \left[\frac{1}{1 - F} \right] \qquad (0 < F < 1)$$

$$= \frac{1}{1 - F} \tag{125}$$

Substituting for $1 - F$ yields

$$E = \frac{1}{(1 - P_d)(1 - P_E') + P_d P_u'} \tag{126}$$

Now throughput is

$$R = \frac{k[(1 - P_d)(1 - P_E') + P_d P_u']}{n + \tau + s} \tag{127}$$

Application of BCH Coding

The overall probability of error for the perfect return channel is

$$\rho = \frac{P_u}{1 - P_d} \tag{98}$$

and the throughput is

$$R = \frac{k(1 - P_d)}{n + \tau + s} \tag{105}$$

For the imperfect return channel, the overall probability of error is

$$\rho = 1 - \frac{1 - P_E}{1 - P_E + P_d P'_u + P_u(1 - P'_E)} \tag{120}$$

and the throughput is

$$R = \frac{k[(1 - P_d)(1 - P'_E) + P_d P'_u]}{n + \tau + s} \tag{127}$$

P_u , P_d , and P_E have already been defined in Eq (86). They should be recognized as the block error probabilities calculated in the last chapter. Since this scheme uses BCH coding, the following substitutions can be made:

$$P_u = PBUE_{BCH} \tag{128}$$

$$P_d = PBDE_{BCH} \tag{129}$$

$$1 - P_E = PBNE_{BCH} \tag{130}$$

where $PBUE_{BCH}$, $PBDE_{BCH}$, and $PBNE_{BCH}$ are given in the last chapter in Eqs (83), (81), and (82) respectively.

Also in the last chapter, the number of information bits, k, and the total number of bits, n, were given

$$k_{BCH} = 8 \text{ NDW} \tag{84}$$

$$n_{BCH} = 20 \text{ (NDW + 2)} \tag{85}$$

where NDW = number of data words.

P'_u and P'_d are given in Eqs (107) and (108) respectively and

$$P'_E = P'_d + P'_u \tag{109}$$

As discussed earlier in this chapter

$$\tau = 12 \tag{131}$$

and

$$s = 20 \tag{132}$$

Now substituting all this information into the general equations for overall probability of error and throughput yields the following results for BCH coding with Stop-and-Wait ARQ and

1. Perfect Return Channel

$$\rho = \frac{PBUE_{BCH}}{1 - PBDE_{BCH}} \tag{133}$$

$$R = \frac{8NDW}{20NDW + 72} (1 - PBDE_{BCH}) \tag{134}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{PBNE_{BCH}}{PBNE_{BCH} + PBDE_{BCH}\ P'_u + PBUE_{BCH}\ (1 - P'_d - P'_u)} \tag{135}$$

$$R = \frac{8NDW}{20NDW + 72} [(1 - PBDE_{BCH})(1 - P'_d - P'_u) + PBDE_{BCH}\ P'_u \tag{136}$$

The results of these calculations for the range of bit error rates considered in this thesis are contained in Appendix D.

IV. Analysis of MIL-STD-1553B Transmissions

Introduction

This chapter contains the analysis for system error and throughput of MIL-STD-1553B with no additional error protection. If an error is detected in a MIL-STD transmission, the message error bit is set (see Appendix A). This is the same bit used for the acknowledgement signal in the stop-and-wait ARQ transmission scheme. With the ARQ scheme, an automatic retransmission occurred whenever the message error bit was set. MIL-STD-1553B does not require a specific bus controller response when the message error bit is set. The system designer is allowed to determine the bus controller's action (Ref 10:3-34). However, the general consensus is to have an automatic retransmission whenever the message error bit is set. For this analysis, we will assume the system is designed accordingly. In this configuration, the system is a stop-and-wait ARQ system and the analysis in the last chapter can be applied.

Perfect Return Channel

As in the perfect return channel analysis of the last chapter, the acknowledgement signal will always be received correctly by the bus controller. The probability of error for the system is

$$\rho = \frac{P_u}{1 - P_d} \qquad (98)$$

where P_u and P_d are the block error rates calculated in Chapter II for MIL-STD-1553B messages with no additional error protection.

$$P_u = PBUE_{M-S} \tag{137}$$

$$P_d = PBDE_{M-S} \tag{138}$$

Now Eq (98) can be written for the MIL-STD-1553B system as

$$\rho = \frac{PBUE_{M-S}}{1 - PBDE_{M-S}} \tag{139}$$

where $PBUE_{M-S}$ and $PBDE_{M-S}$ are given in Eqs (73) and (71) respectively.

Throughput for the perfect return channel stop-and-wait ARQ transmission scheme is given by

$$R = \frac{k(1 - P_d)}{(n + \tau + s)} \tag{106}$$

where τ and s are found in the last chapter for the general case

$$\tau = 12 \tag{131}$$

$$s = 20 \tag{132}$$

P_d is the block detected error rate

$$P_d = PBDE_{M-s} \tag{140}$$

and k and n are found in Chapter II

$$k_{M-S} = 16\ NDW \tag{74}$$

$$n_{M-S} = 20\ (NDW + 1) \tag{75}$$

Now Eq (106) can be written for the MIL-STD-1553B system as

$$R = \frac{4\ \mathrm{NDW}}{5\ \mathrm{NDW} + 13}\,(1 - \mathrm{PBDE}_{M-S}) \tag{141}$$

where PBDE_{M-S} is given in Eq (71).

Imperfect Return Channel

As in the last chapter, this analysis is more realistic than the perfect return channel analysis because it accounts for the possibility of an error in the acknowledgement signal. As calculated in the last chapter, the probability of an undetected error in the acknowledgement signal is

$$P'_u = \sum_{\substack{n=1,3,5,\\ \dots,15}} \binom{16}{n} p_e^{(n+1)} (1 - p_e)^{16-n} \tag{107}$$

the probability of a detected error in the acknowledgement signal is

$$P'_d = \sum_{\substack{n=1,3,5,\\ \dots,17}} \binom{17}{n} p_e^{n} (1 - p_e)^{17-n} \tag{108}$$

and the probability of any error in the acknowledgement signal is the sum

$$P'_E = P'_d + P'_u \tag{109}$$

Then the probability of error for the system, ρ, is

$$\rho = 1 - \frac{1 - P_E}{1 - P_E + P_d P'_u + P_u(1 - P'_E)} \tag{120}$$

where

$$1 - P_E = PBNE_{M-S} \tag{142}$$

$$P_d = PBDE_{M-S} \tag{138}$$

$$P_u = PBUE_{M-S} \tag{137}$$

and P'_u and P'_E are shown above in Eqs (107) and (109) respectively. Equation (120) can be written as

$$\rho = 1 - \frac{PBNE_{M-S}}{PBNE_{M-S} + PBDE_{M-S}\ P'_u + PBUE_{M-S}\ (1 - P'_d - P'_u)} \tag{143}$$

Throughput, R, for the system was shown in the last chapter as

$$R = \frac{k[(1 - P_d)(1 - P'_E) + P_d P'_u]}{(n + \tau + s)} \tag{127}$$

where k, n, τ, and s are the same as for the perfect return channel, P_d is $PBDE_{M-S}$, and P'_E and P'_u are shown in Eqs (109) and (107) respectively. With these substitutions, R is

$$R = \frac{4\ NDW}{5\ NDW + 13}\ [(1 - PBDE_{M-S})(1 - P'_d - P'_u) + PBDE_{M-S}\ P'_u] \tag{144}$$

The results of this chapter are summarized in the following equations for probability of error and throughput for the MIL-STD-1553B system with no additional error protection and

1. Perfect Return Channel

$$\rho = \frac{PBUE_{M-S}}{1 - PBDE_{M-S}} \tag{139}$$

$$R = \frac{4\ NDW}{5\ NDW + 13}\,(1 - PBDE_{M-S}) \tag{141}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{PBNE_{M-S}}{PBNE_{M-S} + PBDE_{M-S}\,P'_u + PBUE_{M-S}\,(1 - P'_d - P'_u)} \tag{143}$$

$$R = \frac{4\ NDW}{5\ NDW + 13}\,[(1 - PBDE_{M-S})(1 - P'_d - P'_u) + PBDE_{M-S}\,P'_u] \tag{144}$$

where $PBDE_{M-S}$, $PBNE_{M-S}$, $PBUE_{M-S}$, P'_u, and P'_d are given in Eqs (71), (72), (73), (107), and (108) repsectively and NDW is the number of data words in a message.

The results of these calculations are included in Appendix D.

V. Analysis of the Hybrid Transmission Scheme

Introduction

A hybrid transmission scheme is a combination of forward error correction and error detection and retransmission. On some communication channels (particularly noisy channels), using only error detection and retransmission results in many retransmissions. The hybrid scheme uses error correction to reduce the number of retransmission requests. A code that is compatible with a hybrid transmission scheme corrects some error patterns (the most likely error patterns) and detects other less likely error patterns. Two coding schemes analyzed in Chapter II can be used with this transmission scheme. They are the Hamming coding scheme and the BCH-hybrid coding scheme. Both schemes correct a small number of errors, and also detect a larger class of errors. The block error rates for both coding schemes are found in Appendix C.

In the analysis of the hybrid transmission scheme by Rocher and Pickholtz (Ref 12), an error free feedback channel was assumed. This led to the results for probability of error

$$P_{UB} = \frac{P_U}{1 - P_D} \tag{145}$$

and throughput

$$R = \frac{k}{n + d + s} (1 - P_D) \tag{146}$$

(Ref 12:428)

where d = retransmission delay = τ.

These two equations should be recognized as equivalent to the probability

of error, ρ, and throughput, R, calculated for the ARQ transmission scheme with a perfect return channel. It makes sense that the hybrid transmission scheme can be analyzed as an ARQ scheme because messages containing detected errors will be retransmitted. However, some of the most likely error patterns will be corrected in the hybrid transmission scheme. In the ARQ scheme, these error patterns would cause a detected error and a retransmission would occur. Therefore, we expect throughput for the hybrid transmission scheme to be higher than the throughput for the ARQ transmission scheme. This will be discussed in more detail in Chapter VII.

Since the hybrid transmission scheme can be analyzed as an ARQ scheme, the results from Chapter III can be used. Thus, the probability of error, ρ, and throughput, R, for the hybrid transmission scheme and:

1. Perfect Return Channel

$$\rho = \frac{P_u}{1 - P_d} \tag{98}$$

$$R = \frac{k}{n + \tau + s} (1 - P_d) \tag{106}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{1 - P_E}{1 - P_E + P_d P'_u + P_u (1 - P'_E)} \tag{120}$$

$$R = \frac{k}{n + \tau + s} [(1 - P_d)(1 - P'_E) + P_d P'_u] \tag{127}$$

With the appropriate substitutions, these equations can be evaluated for the Hamming coding scheme and the BCH-hybrid coding scheme. It was shown in Chapter III, that regardless of the coding scheme

$$\tau = 12 \tag{131}$$

$$s = 20 \tag{132}$$

$$P_d' = \sum_{\substack{n=1,3,5,\\ \ldots,17}} \binom{17}{n} p_e^{\,n} (1 - p_e)^{17-n} \tag{108}$$

$$P_u' = \sum_{\substack{n=1,3,5,\\ \ldots,15}} \binom{16}{n} p_e^{\,n+1} (1 - p_e)^{16-n} \tag{107}$$

$$P_E' = P_d' + P_u' \tag{109}$$

We also know

$$P_u = PBUE \tag{147}$$

$$P_d = PBDE \tag{148}$$

$$1 - P_E = PBNE \tag{149}$$

<u>Hamming Code</u>

The Hamming coding scheme employs (8,4) Hamming codes for the command word - data word pair and a (16,11) Hamming code for each data word. The number of information bits in a message was given in Chapter II as

$$k = 11\ NDW \tag{79}$$

and the total bits in a message is

$$n = 20\ (NDW + 2) \tag{80}$$

The probability of error and throughput for the Hamming coded hybrid transmission scheme and:

1. Perfect Return Channel

$$\rho = \frac{PBUE_H}{1 - PBDE_H} \tag{150}$$

$$R = \frac{11\ NDW}{20\ NDW = 72} (1 - PBDE_H) \tag{151}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{PBNE_H}{PBNE_H + PBDE_H\ P_u' + PBUE_H\ (1 - P_d' - P_u')} \tag{152}$$

$$R = \frac{11\ NDW}{20\ NDW + 72} [(1 - PBDE_H)(1 - P_d' - P_u') + PBDE_H\ P_u'] \tag{153}$$

where $PBDE_H$, $PBNE_H$, and $PBUE_H$ are given in Eqs (76), (77), and (78) respectively.

BCH Code

The BCH coding scheme uses a (31,21,2) BCH code for the command word - data word pair and a (31,16,3) BCH code for the data word - data word pairs. The number of information bits in a message was given in Chapter II as

$$k = 8\ NDW \tag{84}$$

and the total bits in a message is

$$n = 20\ (NDW + 2) \tag{85}$$

The probability of error and throughput of the BCH coded hybrid transmission scheme and:

1. Perfect Return Channel

$$\rho = \frac{PBUE_{BCH}}{1 - PBDE_{BCH}} \tag{154}$$

$$R = \frac{8\ NDW}{5\ NDW + 18}\,(1 - PBDE_{BCH}) \tag{155}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{PBNE_{BCH}}{PBNE_{BCH} + PBDE_{BCH}\ P_u' + PBUE_{BCH}\ (1 - P_d' - P_u')} \tag{156}$$

$$R = \frac{8\ NDW}{5\ NDW + 18}\,[(1 - PBDE_{BCH})(1 - P_d'P_u') + PBDE_{BCH}\ P_u'] \tag{157}$$

where $PBDE_{BCH}$, $PBNE_{BCH}$, and $PBUE_{BCH}$ are given in Eqs (81), (82), and (83) respectively.

The results of these calculations are included in Appendix D.

VI. Analysis of the Forward Error Correction Transmission Scheme

A forward error correction (FEC) transmission system is used when there is no available return channel. The FEC system is designed to correct a certain number of errors, t. Any number of errors greater than t results in an undetected error. Channel codes that correct a given number of errors are suitable for use in this transmission scheme. The BCH coding scheme is suitable when only the error correction potential of the code is used. However, the FEC transmission scheme used within the framework of MIL-STD-1553B is not true FEC for two reasons: (1) the MIL-STD parity bit in each word detects odd errors in the word (pure FEC has no error detection capability); and (2) MIL-STD-1553B requires the use of an acknowledgement signal in the form of the status word (pure FEC has no return channel). By default, the proposed transmission scheme becomes a hybrid transmission scheme.

The hybrid transmission scheme was analyzed in Chapter V. Equations (154) through (157) from Chapter V contain the probability of error and throughput for BCH coding and

1. Perfect Return Channel

$$\rho = \frac{PBUE_{BCH}}{1 - PBDE_{BCH}} \tag{154}$$

$$R = \frac{8\ NDW}{5\ NDW + 18}\,(1 - PBDE_{BCH}) \tag{155}$$

2. Imperfect Return Channel

$$\rho = 1 - \frac{PBNE_{BCH}}{PBNE_{BCH} + PBDE_{BCH}\ P'_u + PBUE_{BCH}\ (1 - P'_d - P'_u)} \tag{156}$$

$$R = \frac{8\ NDW}{5\ NDW + 18}\ [(1 - PBDE_{BCH})(1 - P'_d - P'_u) + PBDE_{BCH}\ P'_u] \tag{157}$$

where $PBDE_{BCH}$, $PBNE_{BCH}$, $PBUE_{BCH}$, P'_u, and P'_d are given in Eqs (81), (82), (83), (107), and (108) respectively. Note that the block error rates should be calculated using the word error rates calculated in Chapter II for the BCH coding scheme using only its error correcting capabilities.

The results of these calculations are included in Appendix D.

VII Results and Conclusions

The results of the analyses presented in Chapters III through VI were used to generate tables of throughput and probability of error. These tables--for various message lengths, bit error rates, and coding-transmission schemes--are contained in Appendix D. In this chapter, the performance characteristics of the different schemes will be compared for the two extreme cases: $p_e = 10^{-4}$ and $p_e = 10^{-7}$.

Throughput (see Figures 7 and 8)

As expected, MIL-STD-1553B without additional error protection (ARQ transmission) has the highest throughput regardless of the bit error rate. The Hamming (hybrid transmission) scheme has the second best throughput, but still has 0.2 to 0.3 less throughput than the MIL-STD scheme (dependent on the message length, but disregarding short ($\leq$ 5 NDW) message lengths). The lowest throughputs are attained by the BCH schemes. When a poor channel ($p_e = 10^{-4}$) is used, the BCH (correction only - FEC transmission) scheme and the BCH (hybrid-hybrid transmission) scheme have essentially the same throughput. Slightly less than these is the throughput of the BCH (detection only - ARQ transmission) scheme. For the better channel ($p_e = 10^{-7}$), all the BCH schemes have essentially the same throughput. This is expected since the significance of the performance gains using a hybrid transmission scheme are inversely proportional to the quality of the channel (Ref 12:426).

Throughput is directly proportional to the message length because there is one command word and one status word for every message

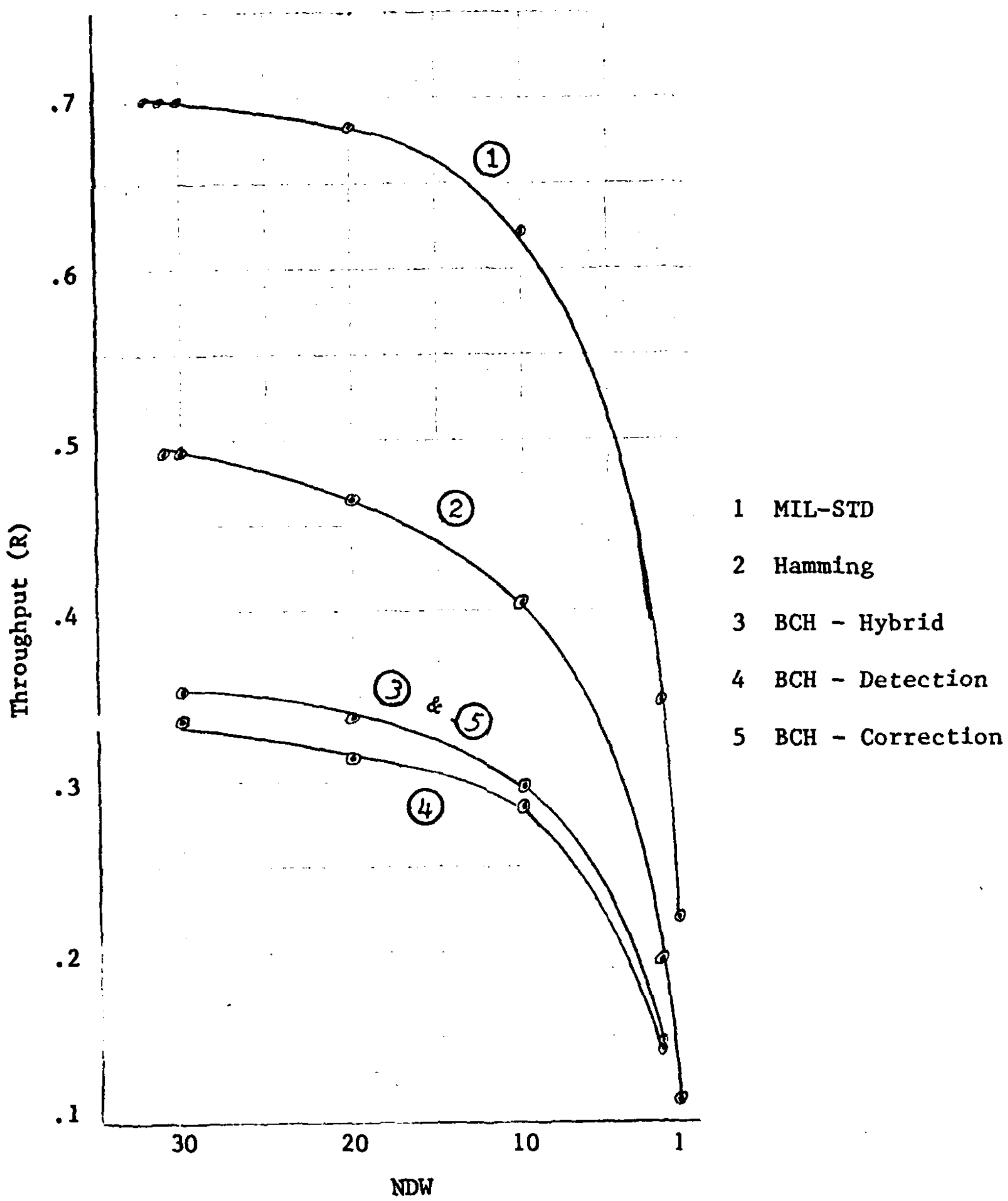


Figure 7. Throughput with Perfect Return Channel and $p_e = 10^{-4}$

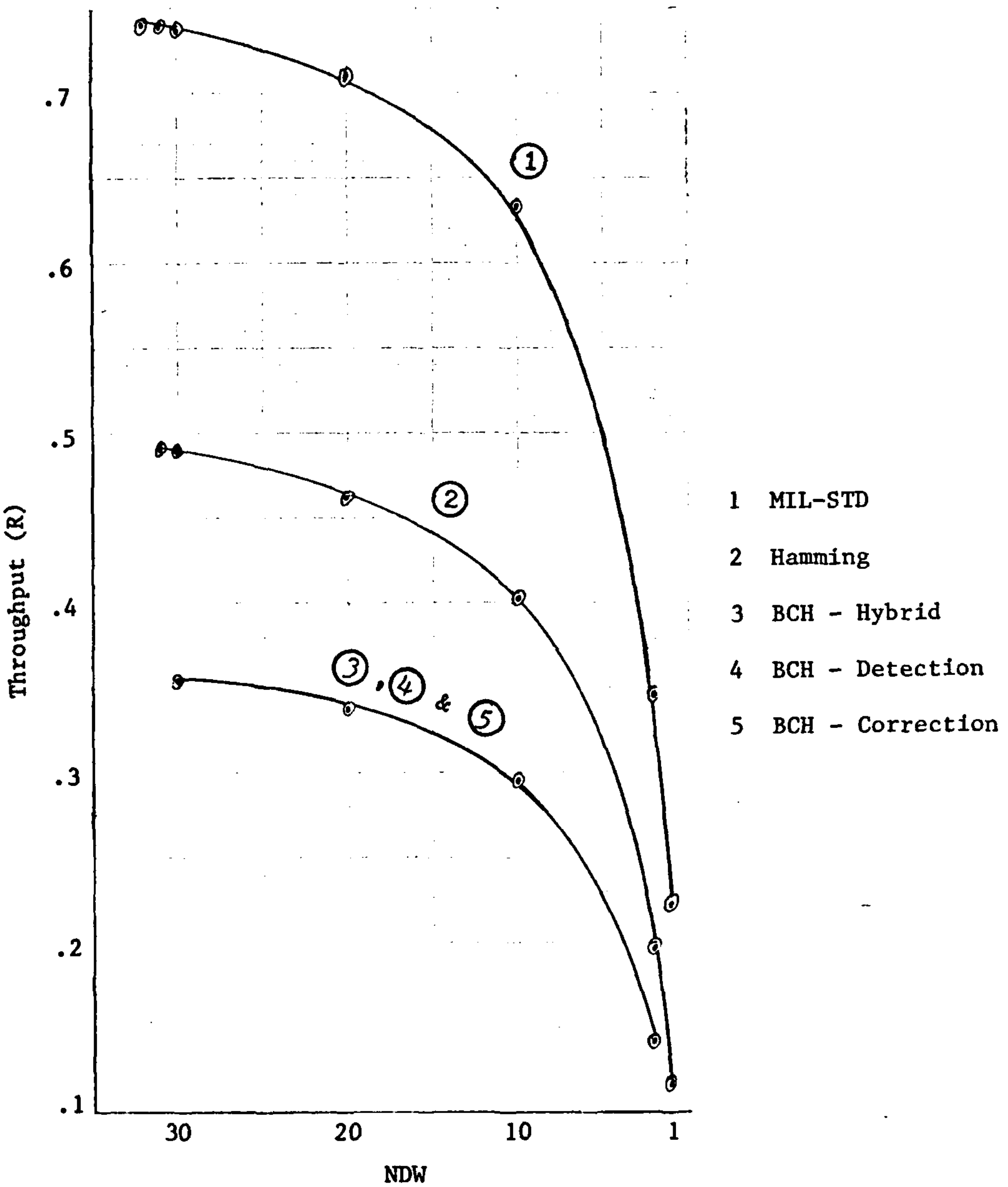


Figure 8. Throughput with a Perfect Return Channel and $p_e = 10^{-7}$

regardless of the message length. Thus, for long messages, the data is a larger percentage of the message, so the throughput increases. Also note that the throughput is virtually unchanged whether a perfect return channel or an imperfect return channel is assumed.

<u>Probability of Error</u> (see Figures 9 - 12)

Because the choice of a perfect or an imperfect return channel affects the probability of error, the two cases will be discussed separately.

For the perfect return channel (see Figures 9 and 10), the BCH (detection only - ARQ) scheme has the best probability of error, but the BCH (hybrid) scheme's probability of error is almost the same. The Hamming (hybrid) and the BCH (correction only - FEC) schemes have the third and fourth best probabilities of error respectively. However, their probability of error is about 10^7 times greater than the best scheme's probability of error for $p_e = 10^{-4}$ and about 10^3 times greater than the best for $p_e = 10^{-7}$. The greatest probability of error occurs for MIL-STD-1553B without additional error protection (ARQ).

For the more realistic case, the imperfect return channel, the BCH (hybrid) scheme has the best probability of error. Its probability of error is about 10^4 times less than the second best scheme for $p_e = 10^{-4}$ and about 10^3 times less for $p_e = 10^{-7}$. The Hamming (hybrid) scheme has the second best probability of error, but the BCH (correction only - FEC) scheme is a close third. The fourth best probability of error belongs to the BCH (detection only - ARQ) scheme. Its probability of error is about 10^7 times greater than the best scheme's probability

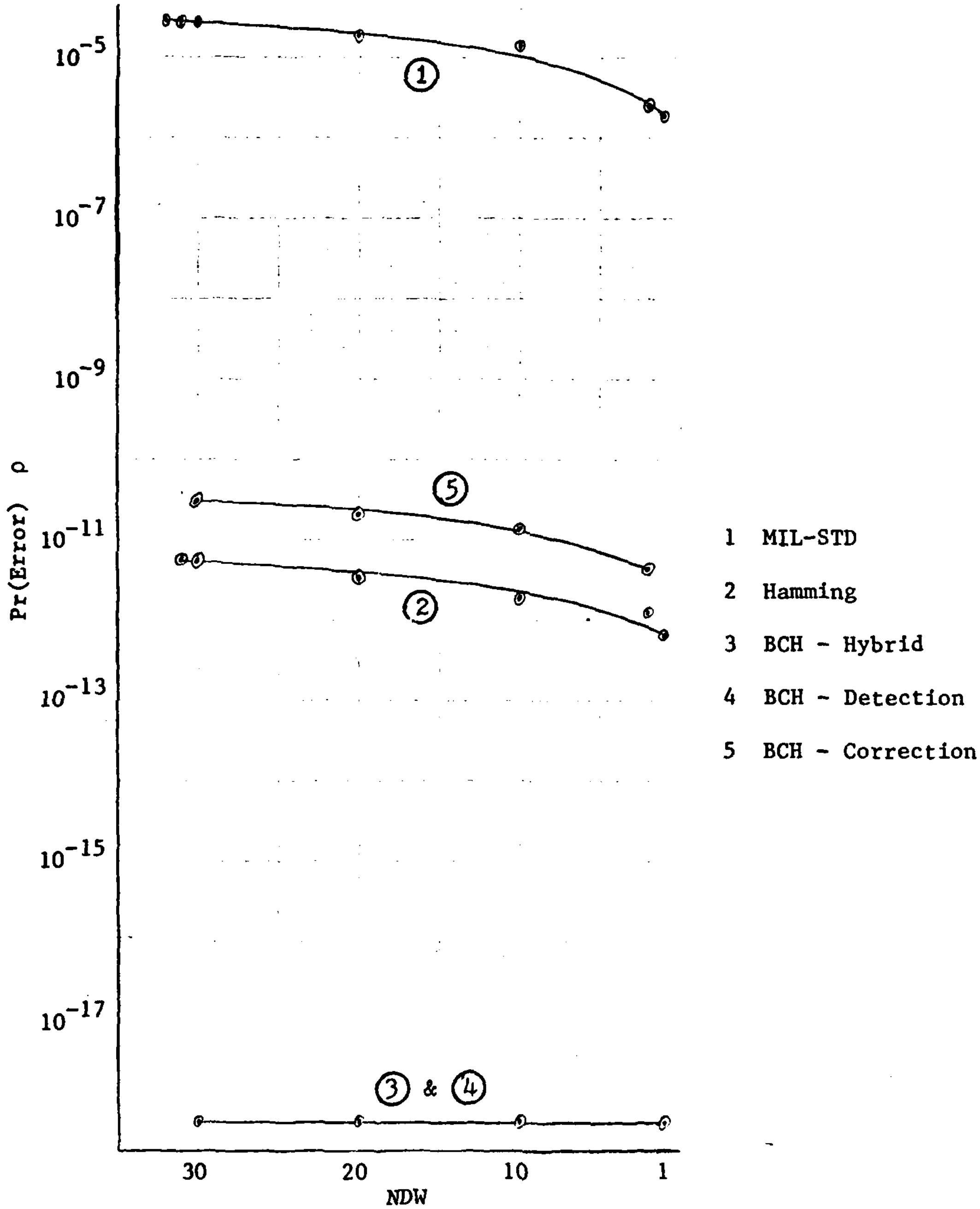


Figure 9. Probability of Error for a Perfect Return Channel with $p_e = 10^{-4}$

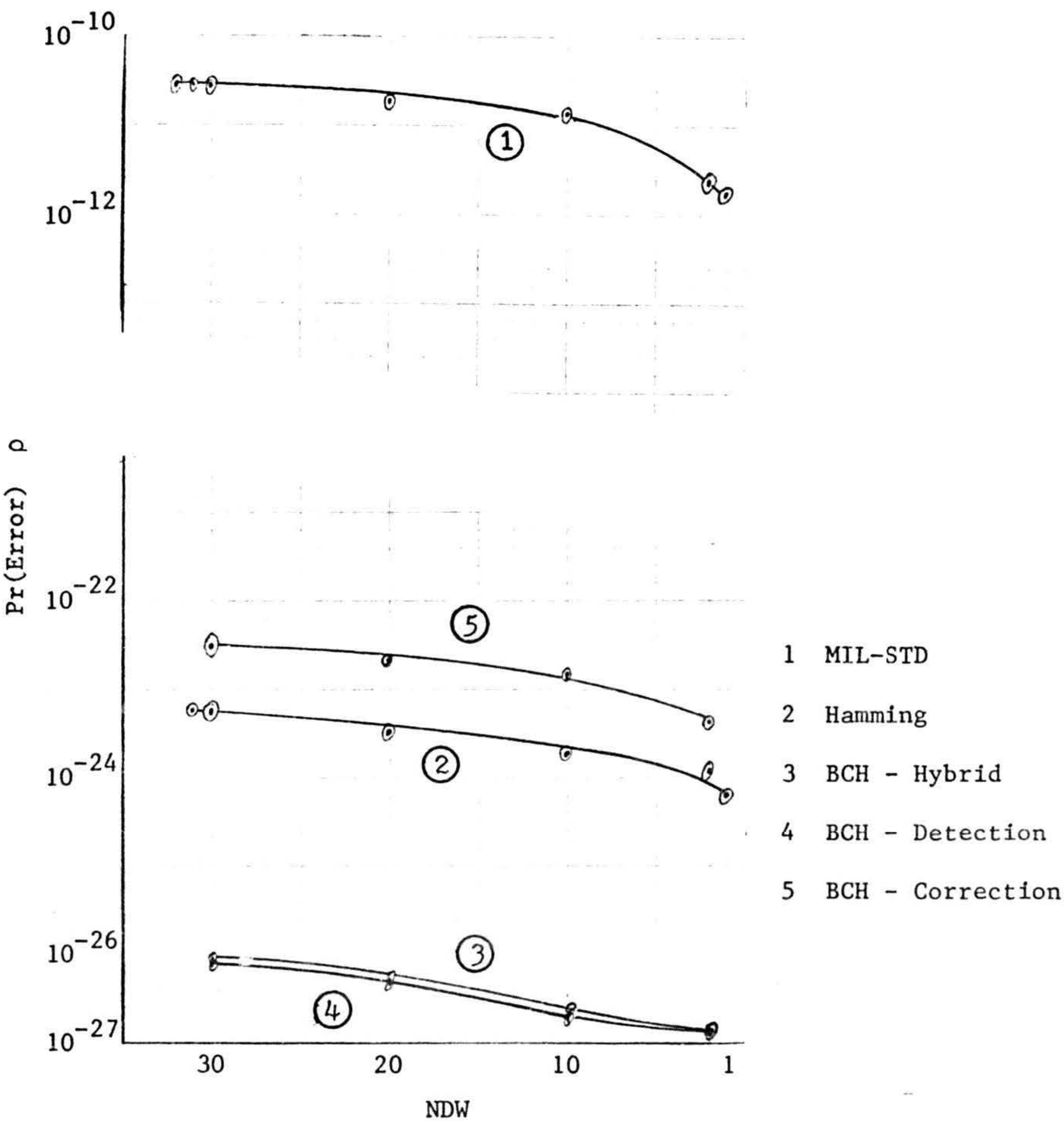


Figure 10. Probability of Error for a Perfect Return Channel and $p_e = 10^{-7}$

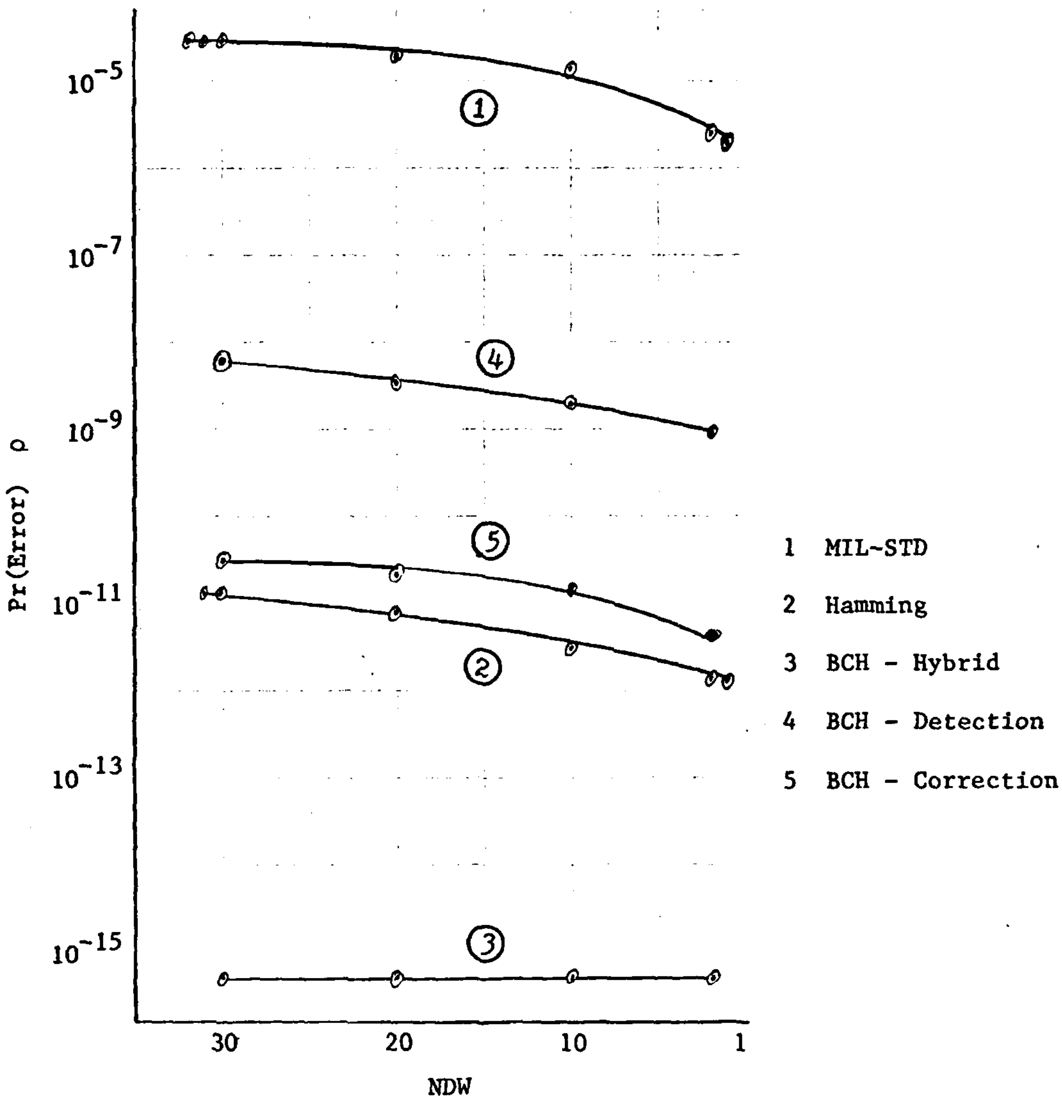


Figure 11. Probability of Error for an Imperfect Return Channel with $p_e = 10^{-4}$

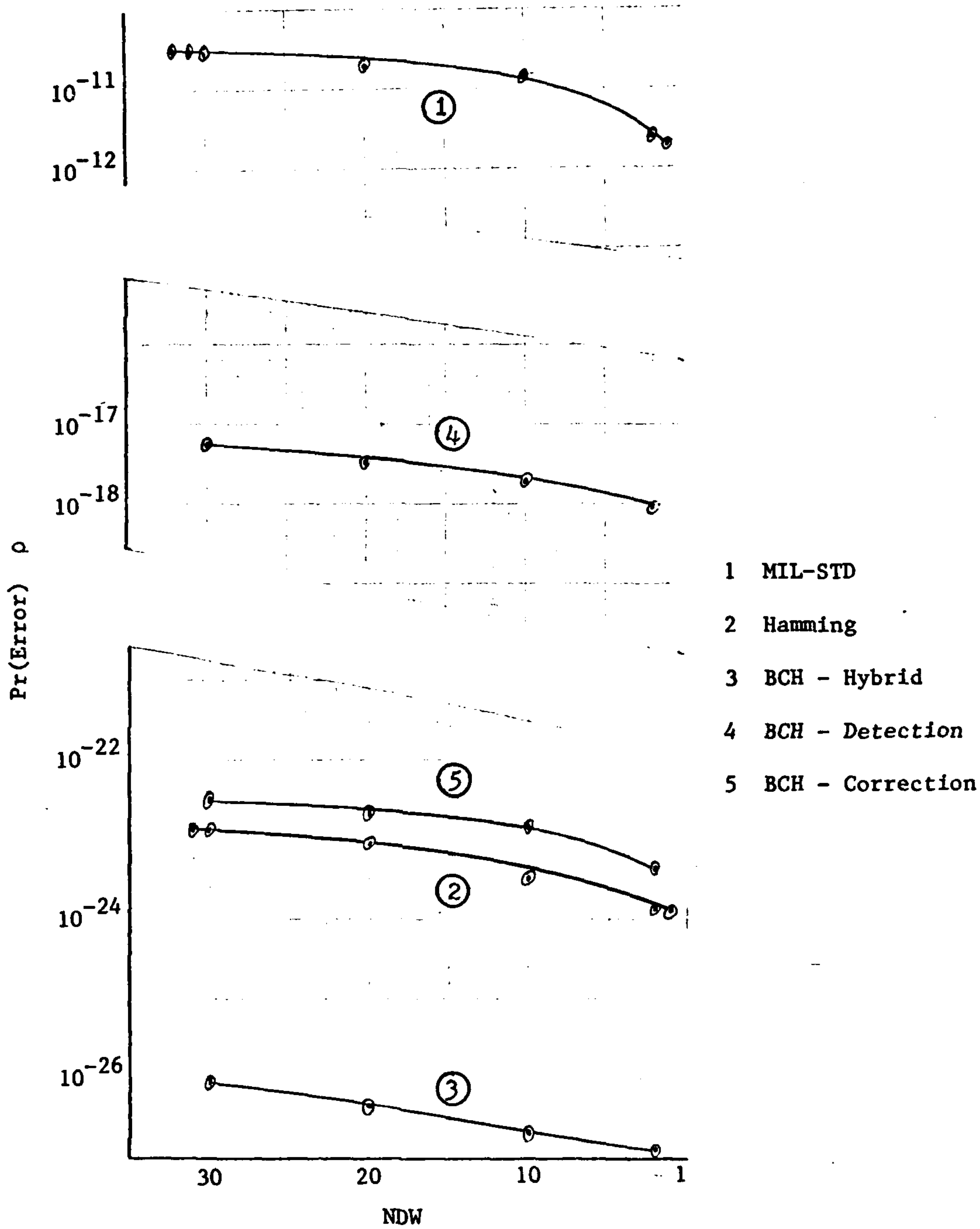


Figure 12. Probability of Error for an Imperfect Return Channel with $p_e = 10^{-7}$

of error for $p_e = 10^{-4}$ and about 10^9 times greater for $p_e = 10^{-7}$. Finally, the MIL-STD (ARQ) scheme has the greatest probability of error. Its probability of error is 10^{10} times greater than the best for $p_e = 10^{-4}$ and about 10^{15} times greater for $p_e = 10^{-7}$.

It is interesting to note the change in probability of error for each scheme when a perfect return channel is assumed and when an imperfect return channel is assumed (see Table I). The only scheme that changes drastically is the BCH (detection only - ARQ) scheme. The errors that occur in the imperfect return channel account for the large change. The MIL-STD (ARQ) scheme does not have a significant change because the imperfect return channel uses the same type of parity check as the original message. The other schemes have small (or zero) change because the number of retransmissions is small.

Table I

Probability of Error Change for a Perfect Return Channel to an Imperfect Return Channel (i.e., ρ_{PRC} x (table I entry) = ρ_{IRC})

Scheme	$p_e = 10^{-4}$	$p_e = 10^{-7}$
MIL-STD (ARQ)	1	1
Hamming (hybrid)	2	2
BCH (hybrid)	10^3	1
BCH (detection only - ARQ)	10^{10}	10^9
BCH (correction only - FEC)	1	1

where: ρ = probability of error

and subscripts: PRC = perfect return channel

IRC = imperfect return channel

Comparison

The overall comparison of the five schemes is summarized for the imperfect return channel in Tables II and III. The return channel cannot be modeled as a perfect return channel because MIL-STD-1553B allows the use of only one bit in the status word for the acknowledgement signal. Thus, errors in the return channel are a possibility. The imperfect return channel analysis accounts for the possible errors. The tables only rank the schemes (1 is the best, 5 is the worst) relative to each other. A system designer should use these tables only as a rough guide. Better comparisons of the systems can be made by using Figures 7 through 12.

Table II

Comparison of Coding-Transmission Schemes with an Imperfect Return Channel and $p_e = 10^{-4}$

Scheme	Pr(Error)	Throughput
MIL-STD (ARQ)	5	1
Hamming (hybrid)	2	2
BCH (hybrid)	1	3
BCH (detection only - ARQ)	4	4
BCH (correction only - FEC)	3	3

Recommendations

This thesis solved the immediate problem of adding additional error protection (within the constraints of MIL-STD-1553B) to a stores management system. There are, however, two areas which may require additional analysis. First, the effect of burst errors on the system

Table III

Comparison of Coding-Transmission Schemes with an Imperfect Return Channel and $p_e = 10^{-7}$

Scheme	Pr(Error)	Throughput
MIL-STD (ARQ)	5	1
Hamming (hybrid)	2	2
BCH (hybrid)	1	3
BCH (detection only - ARQ)	4	3
BCH (correction only - FEC)	3	3

should be investigated. Second, the results of this thesis should be extended to provide probability of error, ρ , and throughput, R , for the entire system. In this thesis, ρ and R are calculated for single messages. To accomplish this extension, message statistics for a stores management system must be developed.

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Appendix A. Salient Features of the MIL-STD-1553B Data Bus (Ref 9)

The development of the MIL-STD-1553 data bus has occurred because of the relatively recent progress in digital technology. The data bus is simply a common communication channel shared by a number of digital processors. One technique for transferring information between these processors is known as time division multiplexing. This type of system (including the MIL-STD-1553 system) is called a multiplex data bus system. The components of the multiplex data bus system are: (1) the bus controller; (2) the remote terminals; (3) the subsystems which may have embedded remote terminals; and (4) the data bus. The data bus conveys information between the bus controller and the remote terminals (RTs). The number of remote terminals on the data bus depends on the complexity of the desired system, but cannot exceed 31 in a MIL-STD-1553 system. The bus controller initiates all information transfers on the data bus and is an integral part of the multiplex data bus system. A subsystem is a functional unit that receives data transfer service from the data bus. Frequently, it is necessary to have more than one data bus; a data bus which has more than one path between the subsystems is called a redundant data bus. According to MIL-STD-1553B (para 20.7), the Air Force will use dual redundant data buses in all applications. Figure 13 illustrates a simple configuration with a dual redundant data bus.

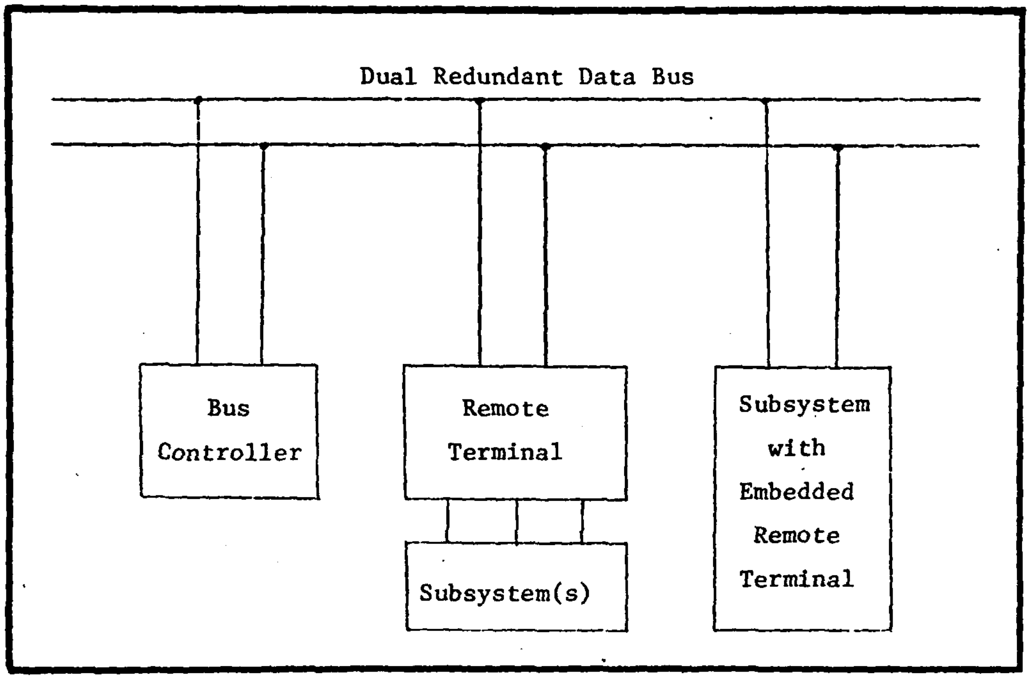

Figure 13. Simple Data Bus Configuration

The Components

1. Subsystem - The subsystem is the functional unit that receives data transfer service from the data bus. In a stores management system, these subsystems control all the aircraft stores. In general, aircraft stores are defined as the complement of weapons and suspension devices which are intended as line replaceable. The data these subsystems receive from the data bus involves the control and communications necessary to provide the pilot with efficient interaction with the aircraft stores.

2. Remote Terminal - The remote terminal is the point of access to the data bus for all subsystems that are part of the multiplex system. The RT performs the control, timing, and signal conditioning

functions that are necessary to interface the subsystem with the data bus. This interface allows the subsystem to send and/or receive data from the bus controller or the other subsystems. Included in the RTs are the multiplex driver/receiver (MDR) units which function as the modems for the communication channel. A maximum of 31 remote terminals is permitted in the MIL-STD-1553 system.

3. Bus Controller - The bus controller is essentially a terminal with the specialized functions of commanding, scanning, and monitoring all data bus traffic. Although a digital computer controls the system through the bus controller, the bus controller has the capability to control the system if the computer fails. The MIL-STD-1553B system contains only one bus controller.

4. Data Bus - The data bus is the transmission medium of the system. It consists of twisted-shielded-pair (TSP) cable with TSP stub transformers to couple each MDR (from the RTs) to the data bus. The Air Force requires the use of dual redundant data buses; therefore, the system must contain at least two data buses and both buses will carry the same message traffic.

Messages and Their Formats

Since this data bus system operates in the command/response mode, all information transfers are initiated by the bus controller. These information transfers take the form of one of six possible message formats (see Figure 14). Each word in these formats consists of 16 bits plus a sync waveform and a parity bit. The three types of words are: command, status, and data. More information on the words will follow. The message formats are as follows:

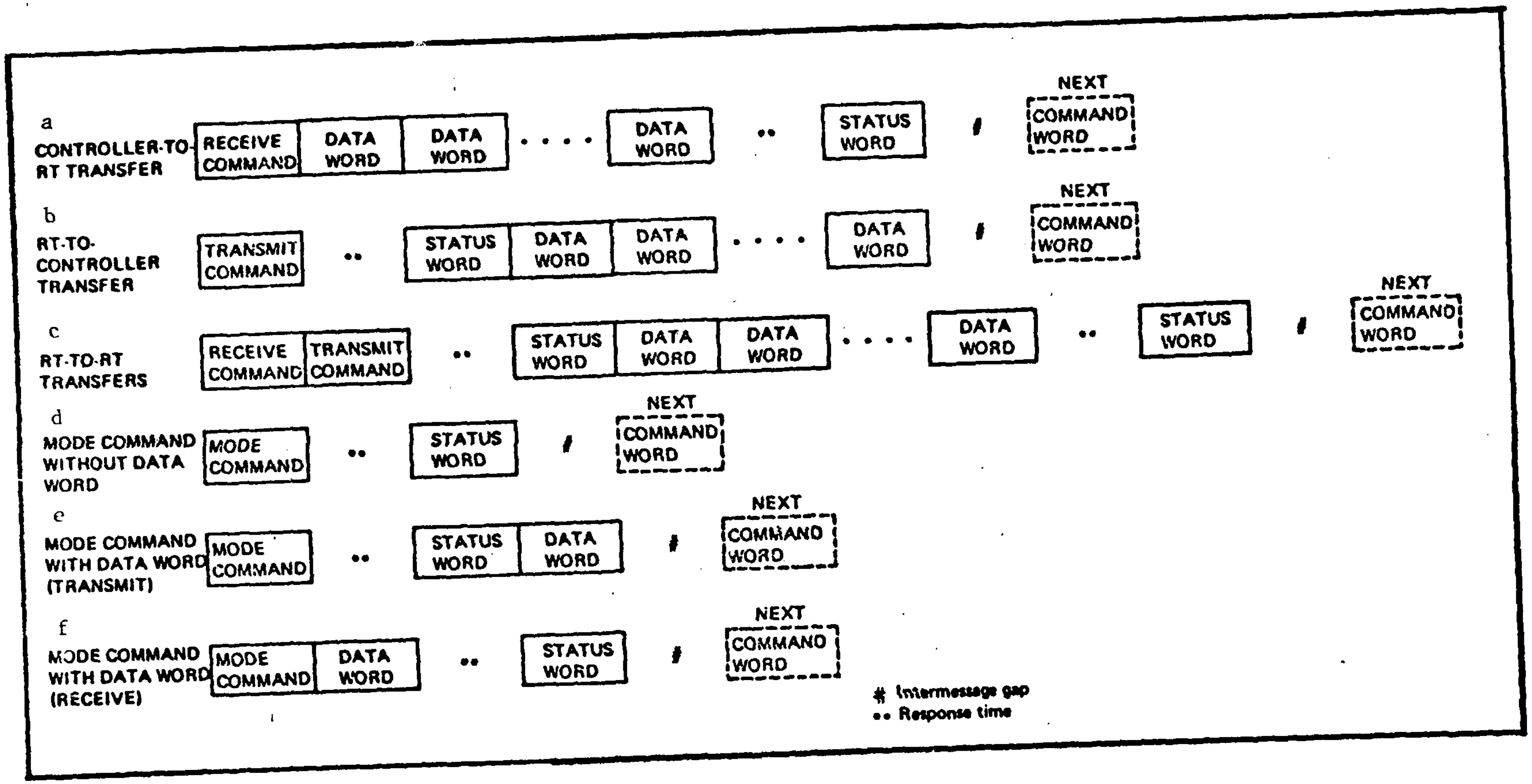

Figure 14. Information Transfer (Message) Formats

Bus controller to RT transfer (Figure 14a)

With this message format, the bus controller sends a specified number of data words ($\leq$ 32) to a specific RT. When the RT has validated the message, the RT sends a status word back to the bus controller.

RT to bus controller transfer (Figure 14b)

The bus controller requests information from a specific remote terminal with this message format. After the RT validates the command word, the RT transmits a status word followed by a specified number of data words ($\leq$ 32) back to the bus controller.

RT to RT transfer (Figure 14c)

This message format is used to transfer information from one RT to another RT. The information transfer is initiated when the bus controller issues a receive command to terminal A followed contiguously by a transmit command to terminal B. After RT B validates the command word, it transmits a status word and a specified number of data words ($\leq$ 32). After RT A has validated the command word and the data words, it transmits a status word to complete the information transfer.

The following three message formats are all mode commands. Mode commands are used only to communicate with the multiplex data bus related hardware and to assist in the management of information flow. Mode commands are not used to extract data from or feed data to a functional subsystem.

Mode command without data word (Figure 14d)

This command uses one of the mode commands as given in Table IV. After the specified RT has validated the command word, the RT will transmit a status word back to the bus controller.

Mode command with data word - transmit (Figure 14e)

This command uses one of the mode commands as given in Table V. The bus controller issues the transmit mode command. After the RT verifies the command, it transmits a status word followed by the required data word to complete the message.

Mode command with data word - receive (Figure 14f)

The bus controller issues a receive mode command from Table V followed by one data word. After the specified RT has validated the command word and the data word, it transmits a status word to the bus controller.

Whenever data words are part of the message, there will be no gaps between any of the words in the string. The response time (** in Figure 14) for the RTs will be within the time period of 4.0 to 12.0 μsec (as measured from the end of the last previous word). If an RT does not respond before 14.0 μsec, then the bus controller will consider the RT did not correctly decode the message. The intermessage gap (# in Figure 14) will be at least 4.0 μsec.

There are also four broadcast type message formats for information transfers. Broadcast messages send information from one source (bus controller or a specific RT) to several RTs at the same time. This does not allow for any closed loop verification that the message

TABLE IV

Assigned Mode Codes With No Data Word

T/R bit	Mode Code	Function	
1	00000	Dynamic Bus Control	(not used by Air Force)
1	00001	Synchronize	
1	00010	Transmit Status Word	
1	00011	Initiate Self Test	
1	00100	Transmitter Shutdown	
1	00101	Override Transmitter Shutdown	
1	00110	Inhibit Terminal Flag Bit	(not used by Air Force)
1	00111	Override Inhibit Terminal Flag Bit	(not used by Air Force)
1	01000	Reset Remote Terminal	
1	01001	Reserved for future use	
	"	" " " "	
	"	" " " "	
	"	" " " "	
1	01111	Reserved for future use	

TABLE V

Assigned Mode Codes With One Data Word

T/R bit	Mode Code	Function	
1	10000	Transmit Vector Word	
0	10001	Synchronize (with data word)	
1	10010	Transmit Last Command Word	
1	10011	Transmit Built-In-Test (BIT) Word	
0	10100	Selected Transmitter Shutdown	(not used by Air Force)
0	10101	Override Selected Transmitter Shutdown	(not used by Air Force)
1 or 0	10110	Reserved for future use	
	"	" " " "	
	"	" " " "	
	"	" " " "	
1 or 0	11111	Reserved for future use	

has been received correctly; therefore, the Air Force will not use the broadcast message formats. Since the Air Force will not use these formats, they will not be presented in this paper.

Word Formats

As mentioned previously, all words in this data bus system consist of 16 information bits, 1 parity bit, and a sync waveform. The information bits and the parity bit will be represented in Manchester II bi-phase level code as shown in Figure 15. Since the system is asynchronous, the timing information for decoding is derived from the sync waveform in each word. The sync waveform is an invalid Manchester waveform of three bit times. The sync for command words and status words is the same (see Figure 16a). The sync waveform for these words is positive for the first 1½ bit times, and then negative for the following 1½ bit times. If the first bit after the sync is a logic zero, then the negative width will appear to be two bit times (see Figure 16a). The sync waveform for data words is shown in Figure 16b and is just the opposite of the command and status word sync waveform. The only other common thing to all three types of words is the parity bit. The last bit in each word is used for odd parity over the 16 information bits in the word. Thus, with 16 information bits, one parity bit, and a three bit wide sync waveform, each word is twenty bit times in length.

Command Word

As shown in Figure 17, the command word begins with a sync waveform and ends with a parity check bit. The information in the command word is contained in the 16 information bits between the sync

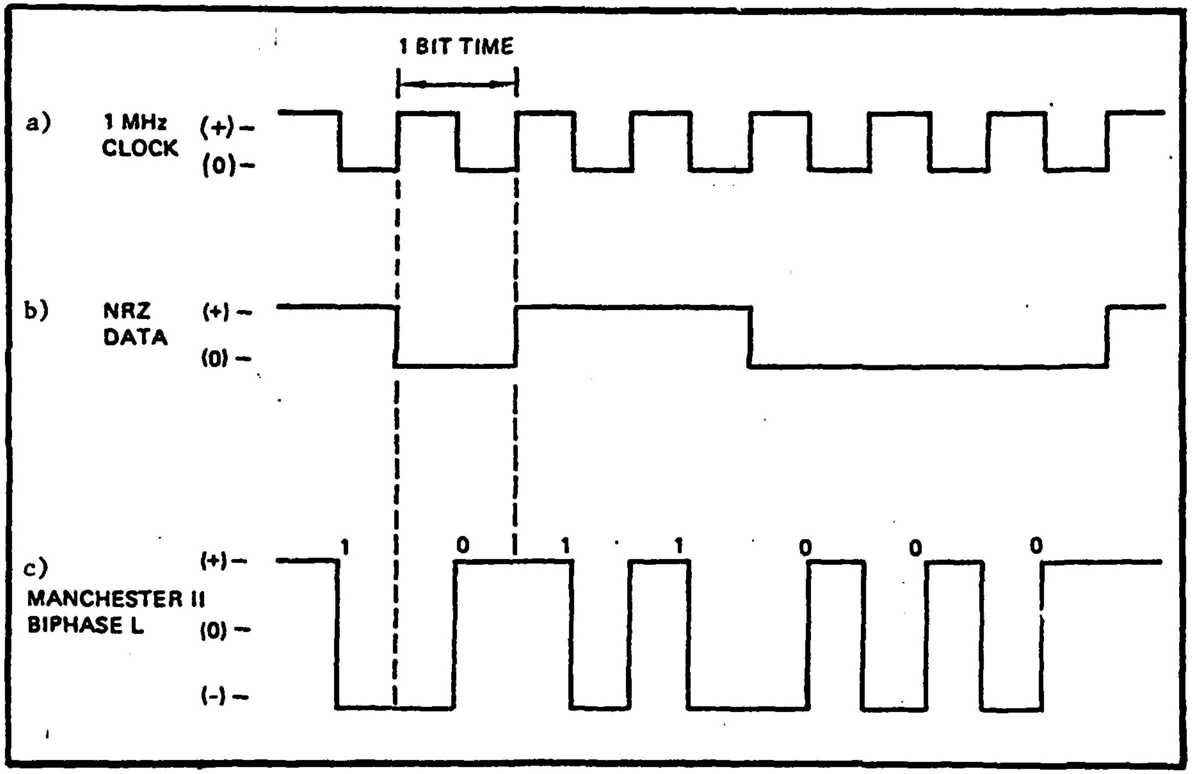

Figure 15. Manchester II Bi-phase Level Encoding

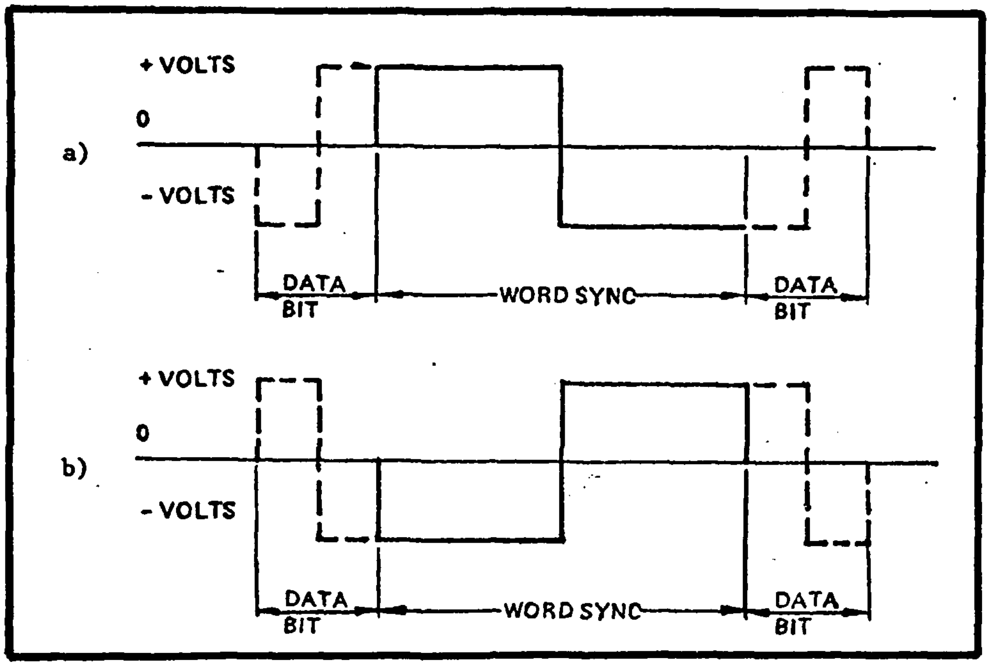

Figure 16. Sync Waveforms: a) Command and Status Word Sync; b) Data Word Sync

waveform and the parity bit. The 16 bits are allocated as follows:

5 bits - RT address field

1 bit - transmit/recieve (T/R) bit

5 bits - subaddress/mode field

5 bits - word count/mode code field

<u>RT address field</u>

The five bits in the RT address field are used to address a unique RT. Decimal address 31 (11111) is used to signify the broadcast option and will not be used by the Air Force. Therefore, 31 unique addresses remain for use as RT addresses.

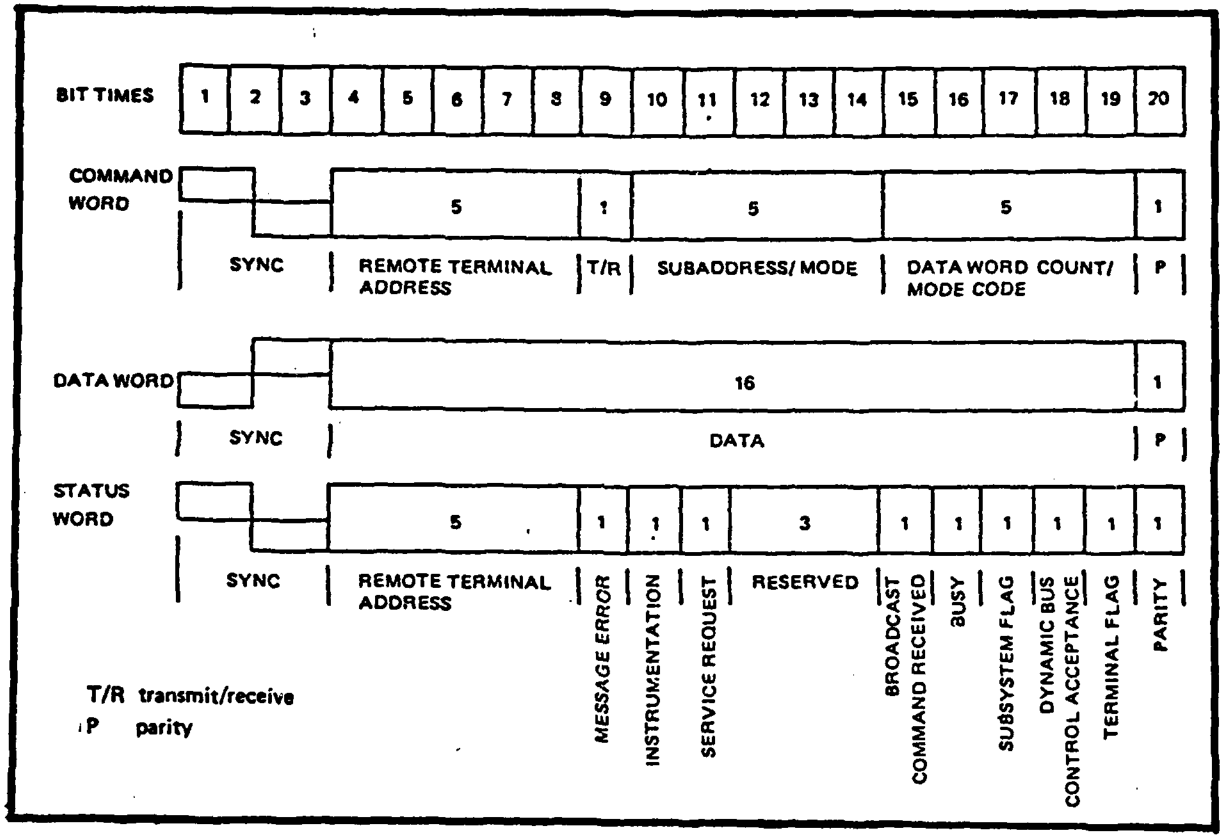

Figure 17. Word Formats

Transmit/receive (T/R) bit

This bit tells the addressed RT whether it is to receive or transmit data. If the bit is a logic zero, the RT will receive data. If the bit is a logic one, the RT will transmit data.

Subaddress/mode field

The five bits in this field are used to indicate a subaddress within the RT or to indicate the use of mode control. If the five bits are all logic zeros or all logic ones, then mode control is indicated. The remaining 30 unique combinations may be used as subaddresses within the addressed RT.

Word count/mode code field

If the previous field was used as a subaddress field, then these five bits are used to indicate the number of data words to be included in the message. The five bits can designate from one to 32 data words with 11111 indicating 31 and 00000 indicating 32. If, however, the previous field indicated the use of mode control, then this field will be decoded as a five bit mode command.

Mode Commands

As previously mentioned, mode codes (see Tables IV and V) are special commands to assist in the management of information transfer. If the first bit of the mode code is a logic zero, then there is no associated data word and the T/R bit is arbitrarily set to a logic one. If the first bit of the mode code is a logic one, then there is one data word associated with the command and the T/R bit is set as

previously specified to indicate the direction of data flow. Some of the mode command codes have been reserved for future use and will not be used. Some of the specified mode commands will not be used by the Air Force. These have been designated in Tables IV and V and will be explained later. The function of each mode code will now be explained.

Dynamic bus control (mode code (MC) 00000)

This mode code is used to transfer control of the bus from the bus controller to an RT capable of bus control. The status word in this message tells the bus controller if the RT will accept control of the bus. This command will not be used by the Air Force because the Air Force will not use dynamic bus control. Air Force systems will have one terminal act as bus controller at all times.

Synchronize without data word (MC 00001)

This mode code causes the RT to synchronize (i.e., reset internal clock). The actual synchronization takes place after a status word has been sent to the bus controller.

Transmit status word (MC 00010)

This mode code causes the RT to retransmit the status word associated with the last valid command word the RT received.

Initiate self test (MC 00011)

This mode code causes the RT to initiate internal testing routines and send a status word back to the bus controller.

Transmitter shutdown (MC 00100)

This mode code is used only when the system has a dual redundant data bus. This mode code causes the RT to shut down the

transmitter associated with the redundant data bus. This command cannot be used to shut down the transmitter associated with the bus from which the command was received.

Override transmitter shutdown (MC 00101)

This mode code is used to enable a previously disabled transmitter. This reverses the action of the previous mode code, so therefore it can be used only with a dual redundant data bus. This mode code cannot enable a transmitter associated with the data bus on which the command was received.

Inhibit terminal flag (MC 00110)

This mode code causes the terminal flag bit in the RT's status word to be held to a logic zero until otherwise commanded. Normally, the terminal flag bit is set to a logic one if an error in the RT is detected. Therefore, the Air Force will not use this mode code because it would bypass the built-in safety factor.

Override inhibit terminal flag bit (MC 00111)

This mode code reverses the action of the previous mode code by returning the terminal flag bit control to the RT. This command will not be used by the Air Force because the terminal flag will never be inhibited.

Reset remote terminal (MC 01000)

This mode code resets the RT to its initialized state (the same state obtained at power-up). The actual initialization takes place after the status word is sent back to the bus controller.

The next six mode commands require one data word to be transferred to or from an RT. For these commands the T/R bit in the command word is set as previously specified to indicate the direction of data word flow (see Table V).

<u>Transmit vector word</u> (MC 10000)

This mode code causes the RT to transmit a status word and one data word containing service request information to the bus controller.

<u>Synchronize with data word</u> (MC 10001)

The command word for this mode code is followed immediately by a data word containing sync information for the RT. After the command and data words are received, the RT will transmit a status word to the bus controller and synchronize.

<u>Transmit last command word</u> (MC 10010)

This mode code tells the RT to transmit the last valid command word received previous to this command. Only the 16 information containing bits (bit positions 4-19) are sent to the bus controller. The data is sent immediately following the status word.

<u>Transmit built-in-test (BIT) word</u> (MC 10011)

This mode code tells the RT to transmit a status word followed immediately by a data word containing the RT BIT data. The BIT data is meant to supplement the bits available in the status word when the RT is complex. NOTE: This data word will not be altered if a transmit last command word or a transmit status word mode code is received before it is used.

Selected transmitter shutdown (MC 10100)

This mode code is the same as the transmitter shutdown mode code except for a system using more than two redundant data buses. The transmitter to be shut down is specified in the data word. However, since the Air Force will only use dual redundant data buses, this command will not be used by the Air Force.

Override selected transmitter shutdown (MC 10101)

This command reverses the action of the previous mode code by enabling a transmitter that was previously disabled. Again the transmitter is specified in the data word and again the Air Force will not use this mode code.

Data Word

As shown in Figure 17, the data word begins with a sync waveform and ends with a parity bit. The 16 information bits are free format. Bit packing is allowed if the information is packaged in less than 16 bit words. If the data words are greater than 16 bits, the most significant bit should be first, followed by less significant bits in descending order of value.

Status Word

As with the command and data words, the status word begins with a sync waveform and ends with a parity bit as shown in Figure 17. The 16 information bits in the status word are allocated as follows:

5 bits - RT address field

1 bit - Message error bit

1 bit - Instrumentation bit

1 bit - Service request bit

3 bits - Reserved for future use

1 bit - Broadcast command received bit

1 bit - Busy bit

1 bit - Subsystem flag bit

1 bit - Dynamic bus control acceptance bit

1 bit - Terminal flag bit

<u>RT address field</u>

The RT address field is the same as previously described for the command word. Each RT has its own unique address. This address tells the bus controller where the status word came from.

<u>Message error bit</u> (mandatory)

The message error bit is set high if the RT detects any errors in the transmission of the command and/or data words. If no errors are detected, the bit is left low.

<u>Instrumentation bit</u> (optional)

If used, this bit is always set low to indicate the word is a status word. This is used because the sync waveforms for the command word and the status word are exactly the same. In the future, the same bit position in the command word may always be set high.

<u>Service request bit</u> (optional)

When this bit is in the high state, it tells the bus controller to take specific actions relative to the RT. If the RT is very

complex, there may be several subsystems that require service. In that case, the subsystem's individual service request signals are ORed into the single service request bit. Then the bus controller must identify the subsystem requesting service through a separate data word. This service request bit will not be used for periodic operations. Only interrupt type operations should be initiated through this bit. In an RT that does not implement this bit, the bit should be set low.

Broadcast command received bit (optional)

This bit, if used, will be set high to indicate that the preceding valid command word was a broadcast command. Otherwise the bit should be set low. It should also be low if it is not used.

Busy bit (optional)

This bit will be set high if the RT cannot transfer data as the bus controller commands. If the RT was to receive data, it will not accept the data words but will respond with a status word. If the RT was to transmit data, the RT will only transmit a status word. In both cases the busy bit would be set high.

Subsystem flag bit (optional)

When this bit is used, it will be set high to indicate a subsystem fault condition. This alerts the bus controller to potentially invalid data. If multiple subsystems are interfaced through a single RT, then each subsystem's fault condition flag will ORed into this single bit to flag the bus

controller. In that case, a separate data word must be used to identify which subsystem contains the fault condition.

<u>Dynamic bus control acceptance bit</u> (optional)

This bit, when high, indicates that the RT will assume the duties of bus controller in response to the dynamic bus control mode code. However, since the Air Force will not use dynamic bus control, this bit will always be set low.

<u>Terminal flag bit</u> (optional)

This bit, when used, will be set high to indicate a fault condition within the RT. If there is no fault condition in the RT or if the bit is not used, the bit will always be low.

With the exception of the RT address all bits in the status word are set to logic zero when a valid command word is received. Two exceptions to this are if the command word contains the mode code "transmit status word" or "transmit last command word." If fault conditions still exist after the status word has been reset, then the error flags will be set again to signal the bus controller of possible errors.

All Terminals

All terminals must validate every word that is received. The terminals must insure that each word; (1) begins with a valid sync field; (2) contains an information field of 16 bits plus parity; (3) has odd parity; and (4) has all the bits in valid Manchester II code. If any of these conditions are not met, then the message error bit should be set. The message error bit will also be set if transmission continuity is not met. The minimum requirements for transmission continuity

are: (1) no interword gaps (i.e., a contiguous message); and (2) properly timed data syncs in relation to the status or command word. Each terminal will also contain a hardware implemented time-out to stop any signal transmission greater than 800.0 μsec. This leaves a buffer for timing inaccuracies since the longest valid message would take 660 μsec to complete. (The longest valid message would be 33 words long. At the MIL-STD-1553 transmission rate of 1 Mbit/sec a 33 word message would take 660 μsec to complete.) If a time-out occurs in an RT, the time-out hardware will be reset on reception of another valid command word of the bus on which the time-out occurred.

Bus Controller

The bus controller may be implemented as a stand-alone terminal or it may be contained within a subsystem. In any case, the responsibilities of the bus controller are: (1) sending data bus commands; (2) participating in data bus transfers; (3) receiving status responses from the RTs; and (4) monitoring system status.

Remote Terminals

The remote terminal will only operate in response to a valid command from the bus controller. A command is valid if it meets all the criteria specified in All Terminals and the command word addresses the RT. If these two conditions are not met, then the command is termed an invalid command and the RT will not respond. An illegal command is a valid command according to the previous definition, but the command contains information that indicates a mode command, subaddress, or word count that has not been implemented in the RT. The RT

will not use information obtained from an illegal command. If the RT receives a valid command word but (1) any of the data words are invalid, or (2) the data word count is incorrect, then an invalid data reception has occurred. If this occurs, the RT will discard the entire message, will set the message error bit, and will suppress the transmission of the status word. An RT can receive a command if:

1. the minimum intermessage gap time since the last message has been exceeded;

2. the RT is not in its response time prior to a status word transmission; and

3. the RT is not transmitting on that data bus.

If the RT receives a second valid command, the second command will take precedence over any previously received commands.

MIL-STD-1553 also includes hardware specifications to be followed when designing a MIL-STD-1553 data bus system. However, since the actual hardware of the bus is not important to this thesis, the hardware discussion has been ommitted.

Appendix B. Word Error Rates

This appendix contains the word error rates. The word error rates are calculated from the equations derived in Chapter 2. The results are presented in order for:

MIL-STD-1553B without additional error protection	- Table VI
Hamming coding scheme - (8,4) command word	- Table VII
Hamming coding scheme - (16,11) data word	- Table VIII
BCH (hybrid) coding - (31,21,2) command word	- Table IX
BCH (hybrid) coding - (31,16,3) data word	- Table X
BCH (detection only - ARQ) - (31,21,2) command word	- Table XI
BCH (detection only - ARQ) - (31,16,3) data word	- Table XII
BCH (correction only - FEC) - (31,21,2) command word	- Table XIII
BCH (correction only - FEC) - (31,16,3) data word	- Table XIV

In all the tables, MSU under the p_e (probability of bit error) heading indicates the bit error rate used in the Mississippi State University Study (Ref 4), i.e., MSU = $2.712182353 \times 10^{-5}$. The notation from Chapter II is also used in the tables:

PNE = probability of no error

PDE = probability of a detected error

PUE = probability of an undetected error

and for the coding schemes that used two MIL-STD words to complete the code:

PNE2 = probability of no error

PDE2 = probability of a detected error

PUE2 = probability of an undetected error

TABLE VI

MIL-STD-1553B Without Additional Error Protection

P_e	PNE	PDE	PUE
.1E-03	.9983013593202379410413570D+00	.1697282718D-02	.1357961665D-05
MSU	.9995390290271152343344360D+00	.4608709729D-03	.1000000001D-06
.1E-04	.9998300135993200233535590D+00	.1699728027D-03	.1359796017D-07
.1E-05	.9999830001359993200493470D+00	.1699972800D-04	.1359979600D-09
.1E-06	.9999983000013599993218770D+00	.1699997280D-05	.1359997960D-11

TABLE VII

Hamming Coding Scheme - (8,4) Command Word

P_e	PNE2	PDE2	PUE2
.1E-03	.9999988804483860327013620D+00	.1119551050D-05	.5640189721D-12
MSU	.9999999176224890750360510D+00	.8237750787D-07	.3058124492D-14
.1E-04	.9999999888004480386362680D+00	.1119955190D-07	.5654416586D-16
.1E-05	.9999999998880004480038650D+00	.1119995520D-09	.5655842453D-20
.1E-06	.9999999999988800004480000D+00	.1119999552D-11	.5662632904D-24

TABLE VIII

Hamming Coding Scheme - (16,11) Data Word

P_e	PNE	PDE	PUE
.1E-03	.9999988011194541746340740D+00	.1198880308D-05	.2376907979D-12
MSU	.9999999117511443625937380D+00	.8824885435D-07	.1287358115D-14
.1E-04	.9999999880011199454016840D+00	.1199888003D-07	.2379690620D-16
.1E-05	.9999999998800011199945410D+00	.1199988800D-09	.2379969060D-20
.1E-06	.9999999999988000011199990D+00	.1199998880D-11	.2379996906D-24

TABLE IX

BCH (Hybrid) Coding - (31,21,2) Command Word

P_e	PNE2	PDE2	PUE2
.1E-03	.9999999955144293126988890D+00	.4485570687D-08	.7344425841D-18
MSU	.9999999999103729711611179D+00	.8962702884D-10	.2928622437D-21
.1E-04	.9999999999955059438480610D+00	.4494056152D-11	.7367901104D-24
.1E-05	.9999999999999955050943940D+00	.4494905606D-14	.7768656479D-27
.1E-06	.9999999999999999955050090D+00	.4494990561D-17	.6035143364D-27

TABLE X

BCH (Hybrid) Coding - (31,16,3) Data Word

P_e	PNE2	PIE2	PUE2
.1E-03	.9999999999968602890824460D+00	.3139710918D-11	.7949303610D-25
MSU	.9999999999999829843377520D+00	.1701566225D-13	.6433260654D-27
.1E-04	.9999999999999996854179570D+00	.3145820430D-15	.6892382447D-27
.1E-05	.9999999999999999999685360D+00	.3146432036D-19	.7680431389D-27
.1E-06	.9999999999999999999999970D+00	.3146493204D-23	.6200461576D-27

TABLE XI

BCH (Detection Only - ARQ) - (31,21,2) Command Word

P_e	PNE2	PDE2	PUE2
.1E-03	.9969046455081448069232130D+00	.3095354492D-02	.7344425841D-18
MSU	.9991595654317988224701200D+00	.8404345682D-03	.2928622003D-21
.1E-04	.9996900464955053138201540D+00	.3099535045D-03	.7367329766D-24
.1E-05	.9999690004649955051182040D+00	.3099953500D-04	.7573064690D-27
.1E-06	.9999969000046499955084260D+00	.3099995350D-05	.5306016262D-27

TABLE XII

BCH (Detection Only - ARQ) - (31,16,3) Data Word

P_e	PNE2	PDE2	PUE2
.1E-03	.99690464550814480692321 3D+00	.3095354492D-02	.7941620505D-25
MSU	.99915956543179882247012 0D+00	.8404345682D-03	.6058451752D-27
.1E-04	.99969004649550531382015 4D+00	.3099535045D-03	.6310887242D-27
.1E-05	.99996900046499550511820 4D+00	.3099953500D-04	.7573064690D-27
.1E-06	.99999690000464999550842 6D+00	.3099995350D-05	.5806016262D-27

TABLE XIII

BCH (Correction Only - FEC) - (31,21,2) Command Word

P_e	PNE2	PDE2	PUE2
.1E-03	.9999999955144293126988890D+00	.4482432671D-08	.3138016219D-11
MSU	.9999999999103729711611179D+00	.8961001567D-10	.1701317047D-13
.1E-04	.9999999999955059438480061D+00	.4493741587D-11	.3145650563D-15
.1E-05	.9999999999999955050943940D+00	.4494874142D-14	.3146415123D-19
.1E-06	.9999999999999999955050090D+00	.4494987414D-17	.3147095019D-23

TABLE XIV

BCH (Correction Only - FEC) - (31,16,3) Data Word

P_e	PNE2	PDE2	PUE2
.1E-03	.99999999999968602890824460D+00	.1694698094D-14	.3138016219D-11
MSU	.9999999999999829843377520D+00	.2491779836D-17	.1701317047D-13
.1E-04	.9999999999999999683541795 7D+00	.1698668289D-19	.3145650563D-15
.1E-05	.9999999999999999999968536D+00	.1699065824D-24	.3146415122D-19
.1E-06	.9999999999999999999999997D+00	.1699105582D-29	.3147111551D-23

Appendix C. Block Error Rates

This appendix contains the block error rates. The block error rates are calculated from the equations derived in the last section of Chapter II. The block error rates are dependent on the number of data words, NDW, in a block (message). Therefore, the block error rates are calculated for a range of block lengths. Again, MSU under the p_e (probability of bit error) heading indicates the bit error rate used in the Mississippi State University study (Ref 4), i.e., MSU = 2.712182353 x 10^{-5} . The order of presentation is:

Coding Scheme	NDW	Table
MIL-STD-1553B without additional error protection:	32	XV
	31	XVI
	30	XVII
	20	XVIII
	10	XIX
	2	XX
	1	XXI
Hamming Coding Scheme:	31	XXII
	30	XXIII
	20	XXIV
	10	XXV
	2	XXVI
	1	XXVII
BCH - Hybrid Scheme:	30	XXVIII
	20	XXIX
	10	XXX
	2	XXXI
BCH - Error Detection Only:	30	XXXII
	20	XXXIII
	10	XXXIV
	2	XXXV
BCH - Error Correction Only:	30	XXXVI
	20	XXXVII
	10	XXXVIII
	2	XXXIX

TABLE XV

Block Error Rates: MIL-STD, NDW = 32

P_e	PBNE	PBDE	PBUE
.1E-03	.94544193455918819052D+00	.5451562459D-01	.4244085270D-04
MSU	.98489962225989377581D+00	.1509712607D-01	.3251672886D-05
.1E-04	.99440567877154513201D+00	.5593874930D-02	.4462982924D-06
.1E-05	.99943915705073484417D+00	.5608384638D-03	.4485491918D-08
.1E-06	.99994390157077073123D+00	.5609838435D-04	.4487749128D-10

TABLE XVI

Block Error Rates: MIL-STD, NDW = 31

P_e	PBNE	PBDE	PBUE
.1E-03	.94705063329069017691D+00	.5290814194D-01	.4122476433D-04
MSU	.98535384177897437109D+00	.1464300363D-01	.3154591362D-05
.1E-04	.99457474295230680761D+00	.5424824200D-02	.4323476770D-06
.1E-05	.99945614766931986611D+00	.5438479810D-03	.4349641863D-08
.1E-06	.99994560147693331668D+00	.5439847955D-04	.4351764128D-10

TABLE XVII

Block Error Rates: MIL-STD, NDW = 30

P_e	PBNE	PBDE	PBUE
.1E-03	.94866206927290438468D+00	.5129792631D-01	.4000441641D-04
MSU	.98580827077663212370D+00	.1418867180D-01	.3057419610D-05
.1E-04	.99474383587656605850D+00	.5255744731D-02	.4193924753D-06
.1E-05	.99947313857674800357D+00	.5268572095D-03	.4213787188D-08
.1E-06	.99994730138598574520D+00	.5269857186D-04	.4215778666D-10

TABLE XVIII

Block Error Rates: MIL-STD, NDW = 20

P_e	PBNE	PBDE	PBUE
.1E-03	.96492800647145839788D+00	.3504442929D-01	.2756423613D-04
MSU	.99036410335080079119D+00	.9633815923D-02	.2080725854D-05
.1E-04	.99643634708704014995D+00	.3563368325D-02	.2845879517D-06
.1E-05	.99964306353848105644D+00	.3569336065D-03	.2854986303D-08
.1E-06	.99996430063545248050D+00	.3569933599D-04	.2855898614D-10

TABLE XIX

Block Error Rates: MIL-STD, NDW = 10

P_e	PBNE	PBDE	PBUE
.1E-03	.98147284247024597505D+00	.1851247166D-01	.1468587318D-04
MSU	.99494099033388358230D+00	.5057914726D-02	.1094940374D-05
.1E-04	.99813173802804813930D+00	.1868112648D-02	.1493235049D-06
.1E-05	.99981301738992760485D+00	.1869811143D-03	.1495723267D-08
.1E-06	.99998130017390892758D+00	.1869981113D-04	.1495972324D-10

TABLE XX

Block Error Rates: MIL-STD, NDW = 2

P_e	PBNE	PBDE	PBUE
.1E-03	.99491272919996653610D+00	.5083210738D-02	.4060062139D-05
MSU	.99861772446610555443D+00	.1381975810D-02	.2997235115D-06
.1E-04	.99949012747917749743D+00	.5098317408D-03	.4078001342D-07
.1E-05	.99994900127497917539D+00	.5099831704D-04	.4079800085D-09
.1E-06	.99999490001274997918D+00	.5099983170D-05	.4079980008D-11

TABLE XXI

Block Error Rates: MIL-STD, NDW = 1

P_e	PBNE	PBDE	PBUE
.1E-03	.99660560402063482459D+00	.3391684668D-02	.2711311796D-05
MSU	.99907827054846831100D+00	.9215295437D-03	.1999078160D-06
.1E-04	.99966005609401646284D+00	.3399167147D-03	.2719129758D-07
.1E-05	.99996600056099401614D+00	.3399916701D-04	.2719912962D-09
.1E-06	.99999660000560999402D+00	.3399991670D-05	.2719991296D-11

TABLE XXII

Block Error Rates: Hamming, NDW = 31

P_e	PBNE	PBDE	PBUE
.1E-03	.99996171586141669411D+00	.3828413065D-04	.7932139487D-11
MSU	.99999718191181102855D+00	.2818088146D-05	.4296610875D-13
.1E-04	.99999961683523745943D+00	.3831647617D-06	.7942479632D-15
.1E-05	.99999999616803517495D+00	.3831964825D-08	.7943489414D-19
.1E-06	.99999999999616800351 7D+00	.3831996483D-10	.7953939357D-23

TABLE XXIII

Block Error Rates: Hamming, NDW = 30

P_e	PBNE	PBDE	PBUE
.1E-03	.99996291469750167172D+00	.3708529480D-04	.7694466728D-11
MSU	.99999727016042576074D+00	.2729839533D-05	.4167875783D-13
.1E-04	.99999962883411306045D+00	.3711658862D-06	.7704510750D-15
.1E-05	.99999999628803405451D+00	.3711965945D-08	.7705492474D-19
.1E-06	.99999999999628830034 05D+00	.3711996595D-10	.7715615011D-23

TABLE XXIV

Block Error Rates: Hamming, NDW = 20

P_e	PBNE	PBDE	PBUE
.1E-03	.99997490313740119625D+00	.2509685728D-04	.5317707800D-11
MSU	.99999815264700141393D+00	.1847352970D-05	.2880523610D-13
.1E-04	.99999974882287698920D+00	.2511771225D-06	.5324821624D-15
.1E-05	.99999999748802285090D+00	.2511977149D-08	.5325523069D-19
.1E-06	.99999999997488002285D+00	.2511997715D-10	.5332497771D-23

TABLE XXV

Block Error Rates: Hamming, NDW = 10

P_e	PBNE	PBDE	PBUE
.1E-03	.99998689[illegible]72102874219D+00	.1310827603D-04	.2940891882D-11
MSU	.99999903[illegible]13435585180D+00	.9648656282D-06	.1593169166D-13
.1E-04	.99999986881165531526D+00	.1311883444D-06	.2945131927D-15
.1E-05	.99999999868801164873D+00	.1311983351D-08	.2945553662D-19
.1E-06	.99999999998688001165D+00	.1311998835D-10	.2949380531D-23

TABLE XXVI

Block Error Rates: Hamming, NDW = 2

P_e	PBNE	PBDE	PBUE
.1E-03	.99999648269141611232D+00	.3517307544D-05	.1039398113D-11
MSU	.99999974112480012753D+00	.2583751942D-06	.5632839743D-14
.1E-04	.99999996480268834218D+00	.3519731155D-07	.1041379758D-15
.1E-05	.99999999964800268303D+00	.3519973120D-09	.1041578131D-19
.1E-06	.99999999999648000269D+00	.3519997312D-11	.1042886738D-23

TABLE XXVII

Block Error Rates: Hamming, NDW = 1

P_e	PBNE	PBDE	PBUE
.1E-03	.99999768156918241604D+00	.2318430016D-05	.8017088277D-12
MSU	.99999829373640707735D+00	.1706263549D-06	.4345482231D-14
.1E-04	.99999997680156811842D+00	.2319843180D-07	.8034107111D-16
.1E-05	.99999999976800156801D+00	.2319984320D-09	.8035811860D-20
.1E-06	.99999999999768000157D+00	.2319998432D-11	.8045876362D-24

TABLE XXVIII

Block Error Rates: BCH-Hybrid, NDW = 30

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999546733364915D+00	.4532666350D-08	.7344437763D-18
MSU	.99999999991011773623D+00	.8988226377D-10	.2928716919D-21
.1E-04	.99999999999550122512D+00	.4498774833D-11	.7472090494D-24
.1E-05	.99999999999999550462D+00	.4495377571D-14	.1231835190D-25
.1E-06	.99999999999999999550D+00	.4495037759D-17	.9693522803D-26

TABLE XXIX

Block Error Rates: BCH-Hybrid, NDW = 20

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999548303220366D+00	.4516967796D-08	.7344433789D-18
MSU	.99999999991020281454D+00	.8979718546D-10	.2928685364D-21
.1E-04	.99999999999550279803D+00	.4497201972D-11	.7437254397D-24
.1E-05	.99999999999999550478D+00	.4495220249D-14	.8456588904D-26
.1E-06	.99999999999999999550D+00	.4495022026D-17	.6664296927D-26

TABLE XXX

Block Error Rates: BCH-Hybrid, NDW = 10

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999549873075818D+00	.4501269241D-08	.7344429815D-18
MSU	.99999999991028789285D+00	.8971210715D-10	.2928653810D-21
.1E-04	.99999999999550437094D+00	.4495629062D-11	.7402670735D-24
.1E-05	.99999999999999550494D+00	.4495062928D-14	.4619569461D-26
.1E-06	.99999999999999999550D+00	.4495006293D-17	.3635071051D-26

TABLE XXXI

Block Error Rates: BCH-Hybrid, NDW = 2

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999551128960180D+00	.4488710397D-08	.7344426636D-18
MSU	.99999999991035595550D+00	.8964404450D-10	.2928628566D-21
.1E-04	.99999999999550562927D+00	.4494370734D-11	.7374650395D-24
.1E-05	.99999999999999550506D+00	.4494[illegible]-14	.1514612938D-26
.1E-06	.99999999999999999551D+00	.4494993707D-17	.1211690350D-26

TABLE XXXII

Block Error Rates: BCH-Detection, NDW = 30

P_e	PBNE	PBDE	PBUE
.1E-03	.95160763223181682349D+00	.4839236777D-01	.7010723694D-18
MSU	.98663747501691906816D+00	.1336252498D-01	.2892008507D-21
.1E-04	.99505225581040983799D+00	.4947744190D-02	.7427914284D-24
.1E-05	.99950412273978801258D+00	.4958772602D-03	.1209165996D-25
.1E-06	.99995040122757978582D+00	.4959877242D-04	.9289626020D-26

TABLE XXXIII

Block Error Rates: BCH-Detection, NDW = 20

P_e	PBNE	PBDE	PBUE
.1E-03	.96647320437165693888D+00	.3352679563D-01	.7120238112D-18
MSU	.99079397013069877175D+00	.9206029869D-02	.2904162014D-21
.1E-04	.99659579045492152786D+00	.3404209545D-02	.7407719444D-24
.1E-05	.99965905796344994444D+00	.3409420366D-03	.8330371159D-26
.1E-06	.99996590057969344948D+00	.3409942031D-04	.6386617889D-26

TABLE XXXIV

Block Error Rates: BCH- Detection, NDW = 10

P_e	PBNE	PBDE	PBUE
.1E-03	.98157099957020299518D+00	.1842900043D-01	.7231463253D-18
MSU	.99496797567973796949D+00	.5032024320D-02	.2916366260D-21
.1E-04	.99814171944524259175D+00	.1858280555D-02	.7387524605D-24
.1E-05	.99981401720394480880D+00	.1859827961D-03	.4543838814D-26
.1E-06	.99998140017204894479D+00	.1859982795D-04	.3483609757D-26

TABLE XXXV

Block Error Rates: BCH-Detection, NDW = 2

P_e	PBNE	PBDE	PBUE
.1E-03	.99381837223571986197D+00	.6181127764D-02	.7321693031D-18
MSU	.99831983719386107244D+00	.1680162806D-02	.2926166815D-21
.1E-04	.99938018906218557618D+00	.6198109378D-03	.7371621169D-24
.1E-05	.99993800189096213073D+00	.6199810904D-04	.1514612938D-26
.1E-06	.99999380001890996219D+00	.6199981090D-05	.1161203252D-26

TABLE XXXVI

Block Error Rates: BCH-Correction, NDW = 30

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999546733364915D+00	.4482458092D-08	.5020825930D-10
MSU	.99999999991011773623D+00	.8961005305D-10	.2722107275D-12
.1E-04	.99999999999550122512D+00	.4493741842D-11	.5033040900D-14
.1E-05	.99999999999999550462D+00	.4494874144D-14	.5034264197D-18
.1E-06	.99999999999999999550D+00	.4494987414D-17	.5035419065D-22

TABLE XXXVII

Block Error Rates: BCH-Correction, NDW = 20

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999548303220366D+00	.4482449618D-08	.3451817827D-10
MSU	.99999999991020231454D+00	.8961004059D-10	.1871448751D-12
.1E-04	.99999999999550279803D+00	.4493741757D-11	.3460215619D-14
.1E-05	.99999999999999550478D+00	.4494874144D-14	.3461056635D-18
.1E-06	.99999999999999999550D+00	.4494987414D-17	.3461849818D-22

TABLE XXXVIII

Block Error Rates: BCH-Correction, NDW = 10

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999549873075818D+00	.4482441145D-08	.1882809725D-10
MSU	.99999999991028789285D+00	.8961002813D-10	.1020790228D-12
.1E-04	.99999999999550437094D+00	.4493741672D-11	.1887390338D-14
.1E-05	.99999999999999550494D+00	.4494874143D-14	.1887849074D-18
.1E-06	.99999999999999999550D+00	.4494937414D-17	.1888280572D-22

TABLE XXXIX

Block Error Rates: BCH-Correction, NDW = 2

P_e	PBNE	PBDE	PBUE
.1E-03	.99999999551128960180D+00	.4482434366D-08	.6276032425D-11
MSU	.99999999991035595550D+00	.8961001816D-10	.3402634094D-13
.1E-04	.99999999999550562927D+00	.4493741604D-11	.6291301126D-15
.1E-05	.99999999999999550506D+00	.4494874142D-14	.6292830243D-19
.1E-06	.99999999999999999551D+00	.4494987414D-17	.6294251743D-23

Appendix D. Probability of Error and Throughput for Various Coding-Transmission Schemes

This appendix contains the results of the equations derived in Chapters III through VI. Probability of Error an Throughput are presented for each coding scheme with both a perfect (PRC) and an imperfect (IRC) return channel and different numbers of data words (NDW). As in the previous two appendices, MSU under the p_e (probability of bit error) heading indicates the bit error rate used in the Mississippi State University study (Ref 4), i.e., MSU = $2.712182353 \times 10^{-5}$. The index to the tables is:

		TABLES	
Coding-Transmission Scheme	NDW	PRC	IRC
MIL-STD without additional error protection:	32	XL	XLI
	31	XLII	XLIII
	30	XLIV	XLV
	20	XLVI	XLVII
	10	XLVIII	XLIX
	2	L	LI
	1	LII	LIII
Hamming:	31	LIV	LV
	30	LVI	LVII
	20	LVIII	LIX
	10	LX	LXI
	2	LXII	LXIII
	1	LXIV	LXV
BCH - Hybrid:	30	LXVI	LXVII
	20	LXVIII	LXIX
	10	LXX	LXXI
	2	LXXII	LXXIII
BCH - Detection Only:	30	LXXIV	LXXV
	20	LXXVI	LXXVII
	10	LXXVIII	LXXIX
	2	LXXX	LXXXI

TABLES

Coding-Transmission Scheme	NDW	PRC	IRC
BCH - Correction Only:	30	LXXXII	LXXXIII
	20	LXXXIV	LXXXV
	10	LXXXVI	LXXXVII
	2	LXXXVIII	LXXXIX

TABLE XL

System Statistics: MIL-STD, PRC, NDW = 32

P_e	P(ERROR)	THROUGHPUT
.1E-03	.448879471790781D-04	.699549133252728D+00
MSU	.330151629391857D-05	.728714265106334D+00
.1E-04	.448808873153381D-06	.735745572306007D+00
.1E-05	.448800896571568D-08	.739469437437208D+00
.1E-06	.448800089749715D-10	.739842886744526D+00

TABLE XLI

System Statistics: MIL-STD, IRC, NDW = 32

P_e	P(ERROR)	THROUGHPUT
.1E-03	.448209670777948D-04	.693361697547701D+00
MSU	.330017502227993D-05	.728378413458524D+00
.1E-04	.448741586361404D-06	.735620514400926D+00
.1E-05	.448794164902869D-08	.739456866646083D+00
.1E-06	.448799416553027D-10	.739841629013512D+00

TABLE XLII

System Statistics: MIL-STD, PRC, NDW = 31

P_e	P(ERROR)	THROUGHPUT
.1E-03	.435277359600077D-04	.699043990469180D+00
MSU	.320147050576525D-05	.727287306844772D+00
.1E-04	.435208607229423D-06	.734091201185702D+00
.1E-05	.435200869432326D-08	.737693826490186D+00
.1E-06	.435200087030322D-10	.738055086836523D+00

TABLE XLIII

System Statistics: MIL-STD, IRC, NDW = 31

P_e	P(ERROR)	THROUGHPUT
.1E-03	.434627777672012D-04	.697857411958159D+00
MSU	.320016983811621D-05	.726952112852049D+00
.1E-04	.435143358687405D-06	.733966424481094D+00
.1E-05	.435194341746186D-08	.737681235883992D+00
.1E-06	.435199434233460D-10	.738053832144765D+00

TABLE XLIV

System Statistics: MIL-STD, PRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.421675228906796D-04	.698430974495200D+00
MSU	.310142470760275D-05	.725750671064718D+00
.1E-04	.421608341120497D-06	.732327059093773D+00
.1E-05	.421600842291235D-08	.735808448680149D+00
.1E-06	.421600034310912D-10	.736157522523787D+00

TABLE XLV

System Statistics: MIL-STD, IRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.421045871017315D-04	.697245436286285D+00
MSU	.310016464649318D-05	.725416185275555D+00
.1E-04	.421545130875003D-06	.732202582247891D+00
.1E-05	.421594518588115D-08	.735795940124895D+00
.1E-06	.421599451913[illegible]D-1[illegible]	.[illegible]6156271057883D+00

TABLE XLVI

System Statistics: MIL-STD, PRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.285652904326762D-04	.683154386341657D+00
MSU	.210096617547187D-05	.701144201116216D+00
.1E-04	.285605669858038D-06	.705441863132738D+00
.1E-05	.285600570778594D-08	.707711905411304D+00
.1E-06	.285600057115785D-10	.707939327903725D+00

TABLE XLVII

System Statistics: MIL-STD, IRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.285226057476727D-04	.681994776665735D+00
MSU	.210011231974351D-05	.700821055970699D+00
.1E-04	.285562845137124D-06	.705321956079268D+00
.1E-05	.285596286931132D-08	.707699874490091D+00
.1E-06	.285599628717311D-10	.707938124408680D+00

TABLE XLVIII

System Statistics: MIL-STD, PRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.149628729461428D-04	.623166684662496D+00
MSU	.110050664242061D-05	.631709260491592D+00
.1E-04	.149602980098844D-06	.633734531651780D+00
.1E-05	.149600299080992D-08	.634801916752794D+00
.1E-06	.149600029918810D-10	.634908762024679D+00

TABLE XLIX

System Statistics: MIL-STD, IRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.149404880054592D-04	.622108898018432D+00
MSU	.110005924577927D-05	.631418116657760D+00
.1E-04	.149580545550344D-06	.633626813006420D+00
.1E-05	.149598055135452D-08	.634791125282720D+00
.1E-06	.149599805519354D-10	.634907682681408D+00

TABLE L

System Statistics: MIL-STD, PRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.408080573468315D-05	.346058013656385D+00
MSU	.300138295316264D-06	.347345399718128D+00
.1E-04	.408008149738389D-07	.347648754177110D+00
.1E-05	.408000815897385D-09	.347808348411464D+00
.1E-06	.408000081598973D-11	.347824313049332D+00

TABLE LI

System Statistics: MIL-STD, IRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.407469507060830D-05	.345470600896136D+00
MSU	.300016247832853D-06	.347185314235675D+00
.1E-04	.407946959044149D-07	.347589662788661D+00
.1E-05	.407994695990413D-09	.347802435758580D+00
.1E-06	.407999469599903D-11	.347823721743890D+00

TABLE LII

System Statistics: MIL-STD, PRC, NDW = 1

P_e	P(ERROR)	THROUGHPUT
.1E-03	.272053900678939D-05	.221468514518318D+00
MSU	.200092206886732D-06	.222017437879174D+00
.1E-04	.272005435008600D-07	.222146685174514D+00
.1E-05	.272000543950086D-09	.222214666851775D+00
.1E-06	.272000054399500D-11	.222221466668518D+00

TABLE LIII

System Statistics: MIL-STD, IRC, NDW = 1

P_e	P(ERROR)	THROUGHPUT
.1E-03	.271646475974484D-05	.221092584996020D+00
MSU	.200010839383121D-06	.221915113885453D+00
.1E-04	.271964640749178D-07	.222108925924933D+00
.1E-05	.271996464007480D-09	.222210889259325D+00
.1E-06	.271999646400074D-11	.222221088892593D+00

TABLE LIV

System Statistics: Hamming, PRC, NDW = 31

P_e	P(ERROR)	THROUGHPUT
.1E-03	.793244317334178D-11	.492755701028104D+00
MSU	.429662298306291D-13	.492773177791824D+00
.1E-04	.794248267488631D-15	.492774377660139D+00
.1E-05	.794348944415227D-19	.492774564585694D+00
.1E-06	.795393935724170D-23	.492774566455105D+00

TABLE LV

System Statistics: Hamming, IRC, NDW = 31

P_e	P(ERROR)	THROUHGPUT
.1E-03	.140354937556375D-10	.491919276572758D+00
MSU	.761004995165719D-13	.492546067140648D+00
.1E-04	.140708516831679D-14	.492690618629739D+00
.1E-05	.140744061809996D-18	.492766187544245D+00
.1E-06	.140850925300594D-22	.492773728739604D+00

TABLE LVI

System Statistics: Hamming, PRC, NDW = 30

Pe	P(ERROR)	THROUGHPUT
.1E-03	.769475209044611D-11	.491053217042730D+00
MSU	.416788716020340D-13	.491070088025230D+00
.1E-04	.770451361004747D-15	.491071246302467D+00
.1E-05	.770549250282325D-19	.491071426748588D+00
.1E-06	.771561501142517D-23	.491071428553200D+00

TABLE LVII

System Statistics: Hamming, IRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.136066654203156D-10	.490219682455915D+00
MSU	.737755098530593D-13	.490843762298727D+00
.1E-04	.136409697075610D-14	.490987776760802D+00
.1E-05	.136444179581392D-18	.491063078660046D+00
.1E-06	.136547657508178D-22	.491070593733029D+00

TABLE LVIII

System Statistics: Hamming, PRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.531784126148630D-11	.466089997227538D+00
MSU	.288052893160836D-13	.466100833860904D+00
.1E-04	.532482296166126D-15	.466101577841172D+00
.1E-05	.532552308257707D-19	.466101693744417D+00
.1E-06	.533249777103626D-23	.466101694903546D+00

TABLE LIX

System Statistics: Hamming, IRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.931839469693152D-11	.465298836269393D+00
MSU	.505256182571500D-13	.465836016032611D+00
.1E-04	.934215007816697D-15	.466022352503983D+00
.1E-05	.934453570934081D-19	.466093770134945D+00
.1E-06	.935167466324370D-23	.466100902531858D+00

TABLE LX

System Statistics: Hamming, PRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.294093043252083D-11	.404406463564841D+00
MSU	.159317070301330D-13	.404411374502871D+00
.1E-04	.294513231327509D-15	.404411711651772D+00
.1E-05	.294555366551841D-19	.404411764175299D+00
.1E-06	.294938053070453D-23	.404411764700576D+00

TABLE LXI

System Statistics: Hamming, IRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.503014693668974D-11	.403720006855925D+00
MSU	.272757358234464D-13	.404224988281482D+00
.1E-04	.504333067909584D-15	.404342972012729D+00
.1E-05	.504465346559112D-19	.404404889278836D+00
.1E-06	.504855833212067D-23	.404411077201612D+00

TABLE LXII

System Statistics: Hamming, PRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.103940176934439D-11	.196427830528875D+00
MSU	.563284120137243D-14	.196428520578087D+00
.1E-04	.104137979456631D-15	.196428564514814D+00
.1E-05	.104157813093533D-19	.196428571359429D+00
.1E-06	.104288673848033D-23	.196428571427880D+00

TABLE LXIII

System Statistics: Hamming, IRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.159956526177378D-11	.196094455500649D+00
MSU	.867583647326635D-14	.196337990063733D+00
.1E-04	.160427532567142D-15	.196395176686930D+00
.1E-05	.160474767261085D-19	.196425232124001D+00
.1E-06	.160607031593205D-23	.196428237499811D+00

TABLE LXIV

System Statistics: Hamming, PRC, NDW = 1

P_e	P(ERROR)	THROUGHPUT
.1E-03	.801710636447080D-12	.119564940187715D+00
MSU	.434548297277737D-14	.119565196990327D+00
.1E-04	.803410729727879D-16	.119565214617579D+00
.1E-05	.803581186214030D-20	.1195652173[illegible]D+00
.1E-06	.804587636229365D-24	.119565217391027D+00

TABLE LXV

System Statistics: Hamming, IRC, NDW = 1

P_e	P(ERROR)	THROUGHPUT
.1E-03	.117074358573129D-11	.119361985579367D+00
MSU	.635084946679248D-14	.119510091455018D+00
.1E-04	.117439341685790D-15	.119544891591667D+00
.1E-05	.117475944722614D-19	.119563184785479D+00
.1E-06	.117576378023933D-23	.119565014130463D+00

TABLE LXVI

System Statistics: BCH - Hybrid, PRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.734443779600130D-18	.357142855524043D+00
MSU	.292871691905110D-21	.357142857110756D+00
.1E-04	.747209049428704D-24	.357142857141250D+00
.1E-05	.123183518959314D-25	.357142857142856D+00
.1E-06	.969352280335579D-26	.357142857142857D+00

TABLE LXVII

System Statistics: BCH - Hybrid, IRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.724872991138248D-15	.356536626070253D+00
MSU	.105773114875550D-17	.356978256133060D+00
.1E-04	.719770725336877D-20	.357082151997508D+00
.1E-05	.842124793541535D-25	.357136785805712D+00
.1E-06	.966827925438372D-26	.357142250000914D+00

TABLE LXVIII

System Statistics: BCH - Hybrid, PRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.734443382204651D-18	.338983049316282D+00
MSU	.292868536461464D-21	.338983050817018D+00
.1E-04	.743725439671231D-24	.338983050845933D+00
.1E-05	.845653390396928D-26	.338983050847456D+00
.1E-06	.666429692730711D-26	.338983050847458D+00

TABLE LXIX

System Statistics: BCH - Hybrid, IRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.722364936134999D-15	.338407645088942D+00
MSU	.105673022429274D-17	.338826819380561D+00
.1E-04	.719518749279797D-20	.338925432404415D+00
.1E-05	.803502163621914D-25	.338977288222371D+00
.1E-06	.663905337834004D-26	.338982474577139D+00

TABLE LXX

System Statistics: BCH - Hybrid, PRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.734442984809171D-18	.294117645734921D+00
MSU	.292865381017818D-21	.294117647032438D+00
.1E-04	.740267073462725D-24	.294117647057501D+00
.1E-05	.461956946097427D-26	.294117647058822D+00
.1E-06	.363507105125842D-26	.294117647058824D+00

TABLE LXXI

System Statistics: BCH - Hybrid, IRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.719856981131851D-15	.293618397949427D+00
MSU	.105572929980473D-17	.293982093286100D+00
.1E-04	.719266778271428D-20	.294067654586184D+00
.1E-05	.765131969191964D-25	.294112647134116D+00
.1E-06	.360982750229135D-26	.294117147059576D+00

TABLE LXXII

System Statistics: BCH - Hybrid, PRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.734442666907934D-18	.142857142215899D+00
MSU	.292862856662901D-21	.142857142844337D+00
.1E-04	.737465039527367D-24	.142857142856501D+00
.1E-05	.151461293802435D-26	.142857142857142D+00
.1E-06	.121169035041947D-26	.142857142857143D+00

TABLE LXXIII

System Statistics: BCH - Hybrid, IRC, NDW = 2

p_e	P(ERROR)	THROUGHPUT
.1E-03	.717850577129343D-15	.142614650434370D+00
MSU	.105492856021938D-17	.142791302453258D+00
.1E-04	.719065195911151D-20	.142832860799004D+00
.1E-05	.734082403962465D-25	.142854714322285D+00
.1E-06	.118644680145240D-26	.142856900000366D+00

TABLE LXXIV

System Statistics: BCH - Detection Only, PRC, NDW = 30

p_e	P(ERROR)	THROUGHPUT
.1E-03	.736724197705403D-18	.339859368654220D+00
MSU	.293117642540065D-21	.352370526791757D+00
.1E-04	.746484844407640D-24	.355375805646575D+00
.1E-05	.120976589091825D-25	.356965758121353D+00
.1E-06	.929008679678343D-26	.357125143295564D+00

TABLE LXXV

System Statistics: BCH - Detection Only, IRC, NDW = 30

p_e	P(ERROR)	THROUGHPUT
.1E-03	.812433106200502D-08	.339282978837624D+00
MSU	.159335300360561D-09	.352208125354868D+00
.1E-04	.795456048592382D-11	.355315400859181D+00
.1E-05	.793785335494570D-14	.356959689794850D+00
.1E-06	.793618531732553D-17	.357124536183735D+00

TABLE LXXVI

System Statistics: BCH - Detection Only, PRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.736723799461878D-18	.327618035380223D+00
MSU	.293114623361455D-21	.335862362756169D+00
.1E-04	.743302301227456D-24	.337829081510143D+00
.1E-05	.833321230150696D-26	.338867477275746D+00
.1E-06	.638683567606346D-26	.338971491721930D+00

TABLE LXXVII

System Statistics: BCH - Detection Only, IRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.554205571505278D-08	.327061924425982D+00
MSU	.109312570033044D-09	.335707569627682D+00
.1E-04	.546452071162036D-11	.337771659215719D+00
.1E-05	.545685122945541D-14	.338861716615383D+00
.1E-06	.545608512087066D-17	.338970915471262D+00

TABLE LXXVIII

System Statistics: BCH - Detection Only, PRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.736723401196715D-18	.288697352814766D+00
MSU	.293111570553599D-21	.292637639905805D+00
.1E-04	.740127825667347D-24	.293571093954483D+00
.1E-05	.454468404711930D-26	.294062946236454D+00
.1E-06	.348367455320332D-26	.294112176521191D+00

TABLE LXXIX

System Statistics: BCH - Detection Only, IRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.299949899422292D-08	.288207306530666D+00
MSU	.594996908305075D-10	.292502768286615D+00
.1E-04	.297833752860831D-11	.293521194384077D+00
.1E-05	.297623362968528D-14	.294057947241649D+00
.1E-06	.297602336519604D-17	.294111676531244D+00

TABLE LXXX

System Statistics: BCH - Detection Only, PRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.736723082575524D-18	.141974124605103D+00
MSU	.293109152643531D-21	.142617119599123D+00
.1E-04	.737619301447428D-24	.142768593437455D+00
.1E-05	.151470684698460D-26	.142848285984423D+00
.1E-06	.116121045196817D-26	.142856257145559D+00

TABLE LXXXI

System Statistics: BCH - Detection Only, IRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.993640171898404D-09	.141733131836247D+00
MSU	.197998885592786D-10	.142551389833439D+00
.1E-04	.992163713682467D-12	.142744331430384D+00
.1E-05	.992016368338260D-15	.142845857600130D+00
.1E-06	.992001637925779D-18	.142856014290287D+00

TABLE LXXXII

System Statistics: BCH - Correction Only, PRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.502082595242375D-10	.357142855541979D+00
MSU	.272210727494823D-12	.357142857110854D+00
.1E-04	.503304090048269D-14	.357142857141252D+00
.1E-05	.503426419675190D-18	.357142857142856D+00
.1E-06	.503541906488331D-22	.357142857142857D+00

TABLE LXXXIII

System Statistics: BCH - Correction Only, IRC, NDW = 30

P_e	P(ERROR)	THROUGHPUT
.1E-03	.501237500102741D-10	.356536626088154D+00
MSU	.272036324503466D-12	.356978256133157D+00
.1E-04	.503219260127154D-14	.357082151997510D+00
.1E-05	.503417933450357D-18	.357136785805712D+00
.1E-06	.503540896746373D-22	.357142250000914D+00

TABLE LXXXIV

System Statistics: BCH - Correction Only, PRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.345181784275797D-10	.338983049327983D+00
MSU	.187144875153175D-12	.338983050817081D+00
.1E-04	.346021561908230D-14	.338983050845934D+00
.1E-05	.346105663514071D-18	.338983050847456D+00
.1E-06	.346184981824637D-22	.338983050847458D+00

TABLE LXXXV

System Statistics: BCH - Correction Only, IRC, NDW = 20

P_e	P(ERROR)	THROUGHPUT
.1E-03	.344603019224020D-10	.338407645100623D+00
MSU	.187059677546575D-12	.338826819380624D+00
.1E-04	.345963465990840D-14	.338925432404416D+00
.1E-05	.346099851691791D-18	.338977288222371D+00
.1E-06	.346184224518168D-22	.338982474577139D+00

TABLE LXXXVI

System Statistics: BCH - Correction Only, PRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.188280973306757D-10	.294117645740458D+00
MSU	.102079022811520D-12	.294117647032468D+00
.1E-04	.188739033768190D-14	.294117647057502D+00
.1E-05	.188784907378196D-18	.294117647058822D+00
.1E-06	.188828057160943D-22	.294117647058824D+00

TABLE LXXXVII

System Statistics: BCH - Correction Only, IRC, NDW = 10

P_e	P(ERROR)	THROUGHPUT
.1E-03	.187968538342851D-10	.293618397954955D+00
MSU	.102033030587676D-12	.293982093286130D+00
.1E-04	.188707671854528D-14	.294067654586184D+00
.1E-05	.188781769983712D-18	.294112647134116D+00
.1E-06	.188827552289964D-22	.294117147059576D+00

TABLE LXXXVIII

System Statistics: BCH - Correction Only, PRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.627603245297524D-11	.142857142216795D+00
MSU	.340263409381908D-13	.142857142844341D+00
.1E-04	.629130112561551D-15	.142857142856501D+00
.1E-05	.629283024341552D-19	.142857142857142D+00
.1E-06	.629425174299379D-23	.142857142857143D+00

TABLE LXXXIX

System Statistics: BCH - Correction Only, IRC, NDW = 2

P_e	P(ERROR)	THROUGHPUT
.1E-03	.626609536361521D-11	.142614650435265D+00
MSU	.340117130205515D-13	.142791302453263D+00
.1E-04	.629030365454724D-15	.142832860799004D+00
.1E-05	.629273045566642D-19	.142854714322285D+00
.1E-06	.629422649944983D-23	.142856900000366D+00

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Stores management systems are being converted from analog control to digital control. The DOD has chosen the MIL-STD-1553B multiplexed digital data bus as the communication channel for the digital stores management system. However, there is insufficient error protection inherent in MIL-STD-1553B to ensure reliable transfer of critical commands. This paper examines possible methods of improving the performance of the system within the constraints of MIL-STD-1553B. To achieve better performance (measured in probability of

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error and throughput), a combination of channel codes and specific transmission schemes are evaluated. Word error rates and block (message) error rates are calculated for each coding scheme. The block error rates are then used to determine the performance of each specific coding scheme-transmission scheme pair. Finally, the coding scheme-transmission scheme pairs are compared for probability of error and throughput. The analysis assumes independent random errors. All calculations are done for a range of bit error rates (10^{-4} to 10^{-7}). Also included in this report is a method of implementing each coding scheme within the constraints of MIL-STD-1553B.